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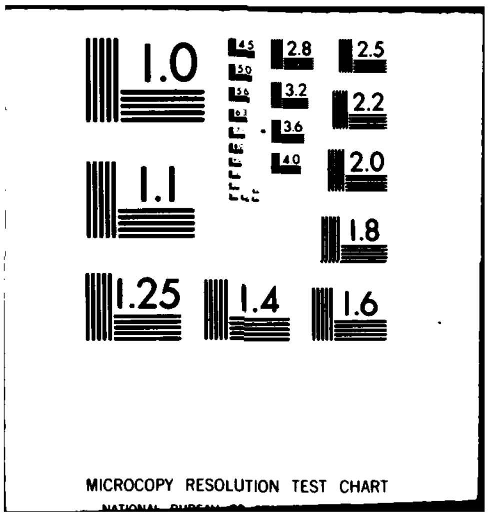
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UNSTEADY PRESSURE MEASUREMENTS ON OSCILLATING MODELS IN EUROPEAN WIND TUNNELS.

Analysis and Optimization Branch
Structures and Dynamics Division

~~March 1980~~
TECHNICAL MEMORANDUM AFWAL-TM-80-1-FIBR

James J. Olsen

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FLIGHT DYNAMICS LABORATORY
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AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

FOREWORD

This work was performed in the Analysis and Optimization Branch, Structures and Dynamics Division, Flight Dynamics Laboratory (AFWAL/FIBR), Wright-Patterson AFB, Ohio. AFOSR Task 2307N5, "Basic Research in Aeroelasticity" supported the effort. The author prepared the manuscript in December 1979 and released it for publication in March 1980.

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SECTION I

INTRODUCTION

The purpose of this report is to summarize the broad aspects of the aerodynamic tests that have been performed over the last twenty years on oscillating bodies and wings in European wind tunnels. While an extensive list of references is available in the open literature, there does not seem to be a general awareness in the United States government or aerospace industry of the intensity and diversity of European efforts. This report gives the background of the development of the major European testing facilities and illustrates the payoffs that have been accrued in the Netherlands, Germany, France and England.

The ability to accurately estimate the aerodynamic forces on oscillating lifting surfaces is an important aspect of the design of modern aircraft. Unsteady aerodynamic calculations are necessary if the designer is to predict the time-dependent aerodynamic maneuver loads on his aircraft, its dynamic stability and handling qualities, its response to gusts, and the speed at which its surfaces could flutter. Modern aircraft continue the drive toward increased aerodynamic loads and performance, with highly stressed structures for efficiency and minimum weight. The inevitable result has been greater structural flexibility, larger deflections and an increased importance of static and dynamic aeroelasticity.

In the aircraft design process it has become increasingly important that potential aeroelastic problems be identified as early as possible. If detection of a flutter problem occurs in the design cycle, the structure must be stiffened, and expensive retooling may be necessary. If problems

appear even later, the designer faces the choice of complete redesign, mass ballasting, or applying speed placards to the aircraft.

In the United States, the initial stages of aeroelastic analyses are done with finite-element structural representations, using sophisticated lifting-surface methods for steady and unsteady aerodynamics. With few exceptions, preliminary aeroelastic considerations are delayed until detailed definitions of the structure are available, at which point preliminary flutter calculations and design tradeoffs may be made. When the design becomes essentially fixed, intermediate aeroelastic calculations are performed and frequently checked with wind tunnel tests on aeroelastic models, even though the analyses have used the most sophisticated methods available. The inertia and stiffness calculations are verified later by ground vibration tests, and the final flutter safety analyses are checked by flight flutter tests on the full-scale aircraft. The unsteady aerodynamic forces, particularly at transonic speeds, are considered to be a weak link in the chain of design and analyses, as contrasted with the greater confidence usually placed in the finite-element structural analysis, the wind tunnel model tests, ground vibration tests and flight flutter tests. There has been little impetus for the development of an additional expensive test technique, i.e. unsteady aerodynamic pressure measurements, because positive tradoffs with aircraft cost and performance have not been readily apparent.

In recent times, European aircraft developers have expressed greater interest in unsteady aerodynamic testing. The capabilities of American and European agencies for mathematical modelling of structures and aerodynamics seem to be roughly comparable, however, the Europeans do not seem to place

as much emphasis on wind tunnel tests with large aeroelastic models. This may have been due to the absence of European test facilities which were comparable to the NASA Langley Transonic Dynamics Tunnel, whose large size and high density allow large aeroelastic models to be built and flutter-tested in the United States. Therefore, in the design stages, Europeans apparently have placed greater reliance on their unsteady aerodynamic computations - hence a strong interest in the experimental facilities that validate those calculations. There is some evidence to indicate that a new U.S. interest in unsteady pressure measurements is being matched by a growth of European interest in flutter models. Both areas are approaching a balanced state which allows design choices to be made on the basis of technological need, rather than being forced into only one type of test by facility limitations.

SECTION II

EUROPEAN EFFORTS

A. The Netherlands

The state-of-the-art of unsteady aerodynamic testing has been accelerated by the contributions from the Netherlands. An experienced team of researchers has been guided by Professor H. Bergh of the National Lucht-en Ruimtevaartlaboratorium (NLR) and the Delft Technological University.

Bergh instituted the "Dutch Tube" system for measuring aerodynamic presures on oscillating wind tunnel models in 1956, at a time when "in situ" strain gage pressure transducers were not small enough or sufficiently advanced to be flush-mounted on the model surfaces.

The "Dutch Tube" system employs orifices and tubing which are conventional for static aerodynamic testing, calibrates the attenuation and phase lags for time-dependent signals, and uses the system for dynamic as well as static tests[1]. While the system was originally conceived out of technical necessity, its major current advantage is its low cost per data point. The low cost comes from the fact that as many as 20 or 30 pressure lines feed into one "scani-valve" and only one expensive transducer. Therefore, while other test facilities can measure perhaps 100 - 200 pressures, the "Dutch Tube" system is set up for as many as 500 static and time-dependent pressure measurements with one system and at comparable costs. As a result, NLR has an unparalled capability for rapid response to test requirements at a relatively low cost. At most other facilities, the measurement system itself is a topic for development. NLR is in a production mode.

The "Dutch Tube" system has not been without temporary development difficulties.

Various measurement techniques and results were discussed by Bergh in References 1 - 7. The calibration of the orifice/tube system remained an empirical experimental procedure until Bergh and Dr Hendrik Tijdeman published[8] their closed form solutions of the linearized Navier-Stokes equations for multiple volume-tube systems in 1965. For small disturbance, laminar flow in long, slender, rigid tubes they obtained analytical expressions for attenuation and phase effects and noted good agreement with experiment, Figure 1.

The apparent success of the tube technique led to its application by Tijdeman to unsteady testing in high subsonic and transonic flows[9] and to the consideration of ancillary factors, such as the extrapolation of measured data to oscillatory modes of motion other than those tested[10]. Using one experimental mode shape, Bergh and Zwaan developed families of correction factors to apply to theoretical results for other mode shapes (Figure 2) and checked their technique for theoretical/experimental data on a stabilizer and a fin (Figures 3 and 4) in four different rigid-body modes. They noted reasonable success, particularly when only small corrections were necessary when the theoretical predictions qualitatively reflected the experimental data.

Tijdeman and Bergh then followed with one of their most important and widely quoted papers[11] on the two-dimensional NACA 64A006 (mistakenly identified as a 65A006) airfoil with an oscillating flap. They presented the mean steady flow and fundamental harmonic unsteady results for frequencies up to 120 Hz for Mach numbers of 0.5 to 1.02 in the NLR pilot tunnel (Figures 5 and 6). The measurement technique was still new and controversial. The authors took pains to estimate the probable experimental error, but indicated

they were not able to assess the dynamic effects of wind tunnel wall interference. Tests on more elaborate three-dimensional surfaces[12-14] followed soon thereafter (Figures 7 - 9)

Stimulated by interest from the NATO/AGARD community, NLR undertook several tests on three-dimensional wings with oscillating control surfaces[15-17]. Cooperative subsonic and supersonic pressure measurements were obtained on a variety of planar wings with full span and partial span oscillating control surfaces (Figures 10 - 13).

The first hint that some additional development was necessary arose in the joint testing of a swept wing (Figure 14) by NLR and ONERA of France[18]. It turned out that a new nonlinearity was introduced by the particular type of entrance ports used for the pressure tubes. It was known that the tube transfer functions depended on the ambient <u>static</u> pressure and frequency, but for this test they also depended in a nonlinear way on the <u>amplitude</u> of the time-dependent pressure (Figure 15). This new facet required a more extensive calibration of the NLR tube system, which then gave good agreement with low speed data from the ONERA transducers. The ONERA tests were possible because by 1972 "in situ" transducers had been developed sufficiently to allow their use on the same model and comparison with NLR's tube data. Notwithstanding the difficulties experienced, Figure 14 is a good illustration of the cost-advantages and detailed pressure coverage available with the tube system.

Subsequently Bergh and Tijdeman found[19] that their entire calibration process had been satisfactory only for relatively low speed flows and that the tube calibration depended on the rate of free stream flow past the orifice. The miniscule flow into and out of the pressure orifices altered the

streamlines near the orifices and subsequently the pressures (Figure 16). The tube calibration now had to be done in a flowing air. Calibrations in static air could be inaccurate. On the positive side, they also determined that there were no apparent effects of subsonic flow, supersonic flow, shocks, or the model boundary layer on the tube calibrations. With the new pressure correction formulas, the NLR tubes gave excellent agreement with ONERA's flush mounted pressure transducers. The modified pressure measurement system was then applied by Tijdeman and Schippers to a lifting two-dimensional airfoil with an oscillating flap[20]. Tijdeman and Mr Roger Destuynder of ONERA presented their comforting agreement to AGARD in a joint publication[21] (Figure 17). The agreement with the available theories was also good, except that both sets of pressure data showed systematic discrepancies between theory and experiment in the out-of-phase component of unsteady pressure.

Another aspect of the joint paper by Tijdeman and Destuynder was that ONERA and NLR each performed flutter tests in their own wind tunnels on the same model that was used for the unsteady pressure measurements (Figure 14). Agreement was good between the experimental flutter data of ONERA and NLR. Theoretical predictions gave slightly conservative results, that is, the predicted flutter speeds were slightly lower than the experimental flutter speeds. A rather disturbing aspect, however, was the results of the use of the "Modal correction matrix" of Bergh and Zwaan[10]. The use of measured unsteady pressures for one mode, in conjuction with a correction matrix to convert the pressures from the mode to the flutter mode, gave unconservative flutter results (Figure 18).

At that point, NLR and the rest of the AGARD community were confident

in the "Dutch Tube" system. NLR applied the corrections for amplitude effects and local flow to their measurement system, undertook some new measurment programs[22], and published corrected data[23,24] from some of their earlier tests on the NACA 64A006 airfoil with oscillating flap (Figure 19). The "Dutch Tube" system became recognized as reliable and accurate, and its cost advantages could then be safely exploited.

NLR then demonstrated the capability[25] for enormous numbers of pressure measurements on sophisticated models (Figures 20 and 21). In a remarkable subsonic test on an NF-5 wing with external stores, NLR was able to measure static, quasi-steady, and unsteady, and unsteady pressures at 176 points on the wing, 86 points on a pylon and 78 points on a tip tank - all with the same set of orifices, tubes and scani-valves. They also hit upon a new key idea for their calibration process. They installed a small number (perhaps 8 or 10) flush mounted pressure transducers along one entire chord line of the model, adjacent to a matching set of tube orifices. Those "in situ" transducers were taken as "exact" pressures and were used to generate the calibration transfer functions for the adjacent tubes. Since the transducers were mounted along an entire chord, they were able to span a large variation in static and dynamic pressures. Hence, a few transducers produced calibrations for the entire system of 340 tubes.

In 1975 the well established confidence in their measurement system allowed Bergh, Tijdeman, and their coworkers to conduct transonic pressure measurements on oscillating wind tunnel models and concentrate on the physics of transonic unsteady flow. There followed a remarkable series of papers by Tijdeman[26-34]. He reexamined the steady, quasi-steady and unsteady flow over the NACA 64A006 airfoil with oscillating flap (Figure 22) and elucidated three

types of shock motion:

A. The relatively strong shock which oscillates through small amplitudes about a fixed mean position.

B. The weaker shock which moves forward on the airfoil to disappear, only to reappear at an aft location and move forward again.

C. The weakest shock which moves forward on the airfoil but continues to propagate forward in the subsonic free stream.

He also was able to thoroughly investigate the transonic flow over the "supercritical" NLR 7301 airfoil (Figure 23). He noted the opposite effects of thickness and the boundary layer (Figures 24 and 25). Most importantly, he discerned four flow regions of importance for the supercritical airfoil. In the fully subsonic region theory and experiment were in good agreement. In the slightly supercritical transonic region the overall agreement between experiment and thin airfoil theory was good, except for a small supercritical region at the nose. In the strongly transonic region with fully developed shock wave, linear thin airfoil theory failed completely to reflect the unsteady pressure distribution near the shock. In the "shock free" design condition around the airfoil's design point, the quasi-steady pressures on the upper surface had a wide bulge (Figure 26) which produced large deviations between the then available linearized theories and the unsteady test data.

The success of the "Dutch Tube" system has lead to great confidence in their results. Building on the NLR success with the subsonic NF-5 model[25,35] the United States AFFDL sponsored NLR in an extensive subsonic, transonic, transonic and supersonic test program for the F-5/F-16 wing, Figure 27. A careful steady, quasi-steady and unsteady test program[38,38] was conducted

for a build up of components (clean wing, launcher, missile body, missile fins), for frequencies of 0, 10, 20 and 40 Hz and for Mach numbers of 0.6, 0.8, 0.9, 0.95, 1.05, 1.1, 1.2 and 1.35. These tests will be followed in 1980 with AFFDL-sponsored tests on the same F-5/F-16 wing with an oscillating flap. In 1981 tests on a three-dimensional supercritical transport wing will be conducted by NLR in a joint program with the AFFDL, NASA Langley and the Lockheed-Georgia Company.

Finally, NLR has recently updated their tube measurement system[39] to allow the resolution of higher harmonics of the test data, as seen in Figure 28 for an NLR 7301 airfoil with oscillating flap.

B. Federal Republic of Germany

The initial German efforts in unsteady pressure measurements came about in 1963 when Dr B. Laschka of the then Entwicklungsring Sud consortium sponsored pressure measurements on a complicated wing-store configuration[42]. The actual measurements were conducted by Bergh and Cazemier of NLR in the Netherlands[40,41] with their tube system. These may have been the first unsteady pressure measurements on a finite span wing. The model consisted of an aspect ratio 1.45 wing with a complicated dual engine configuration at the wing-tip (Figure 29). The bare wing later became one of the first AGARD standard configurations.

The model was oscillated in pitch, heave, roll, aileron rotation and flap rotation. At reduced frequencies (based on semispan) less than 2.67 agreement between the experimental data and the existing lifting surface theory was good. However, large discrepancies in the out-of-phase components appeared at higher reduced frequencies. It turned out that the errors did not depend on the non-dimensional reduced frequency $\frac{s\omega}{V}$ so much as they did on the dimensional frequency, ω. This may have been an indication of early problem in the calibration

of the tube system.

In 1967 Hertrich and Wagener[43] installed the "Dutch Tube" system at the Deutsche Forschungs-und Versuchsanstalt fur Luft-und Raumfahrt (DFVLR) - Aerodynamische Versuchsanstalt-Institute fur Aeroelastik (AVA) in Gottingen. They also added automation features with respect to rapid scanning, calibration and storage of the large quantitites of data.

Becker[44] and Triebstein[45] followed with a series of tests on oscillating wings and wing/control combinations. Some of the results were reported to AGARD in 1970 by Forsching, Triebstein and Wagener[46]. In particular, they investigated the singularities which theory predicted would occur at the edges of oscillating control surfaces. The model (Figure 30) was a 25° swept wing aspect ratio of 2.94 and an NACA 0012 airfoil section. The twin control surfaces were contained in the last 30% of the constant chord, and the model also could be pitched about an axis normal to the wind tunnel wall. The experimental results tended to confirm the predicted singularities in pressure distribution, particularly in the spanwise direction.

Triebstein and Becker[47] and Triebstein and Wagener[48] conducted pressure measurements with the tube system on a combination of a harmonically oscillating, variable-sweep wing and a stabilizer (Figure 31) in incompressible flow. Triebstein[49] extended the oscillating wing measurements to subsonic compressible flow. Becker[50] and Forsching[51] presented some of the data to AGARD, summarizing the test variables in Table 1. They obtained fascinating experimental data on wing-tail interference, including the self-induced pressures on the forward wing due to wing pitch and on the tail due to tail pitch. They were also able to measure the pressures induced on the tail by wing pitch, with variations with tail position and wing sweep. They got relatively good agreement between theory and experiment, except for the case of 70° wing

sweep, which they attributed to the large vortices from the wing which were not accounted for in the theory. They also found that the measured pressures induced on the wing due to tail pitch were consistently less than theory predicted. They experienced some difficulty in precisely measuring the amplitudes of the surface motions and attributed some data uncertainty to that cause. Forsching[51] also discussed the general requirements for a good unsteady pressure measurement program, including the requirement for accounting for flow effects and other nonlinearities on calibration of the tube system. He gave a concise comparison of the relative features and benefits of the tube system when compared to the "in situ" transducer methods which had become available.

Triebstein[52,53] performed unsteady pressure measurements on an oscillating body of revolution and on a rotor blade at static incidence. Geissler[54] also presented those results along with numerical predictions from his singularity method which satisfied the exact boundary conditions on the body surfaces (Figures 32 and 33).

In his Theodorsen commemorative paper Forsching[55] gave a brief summary of the many results obtained in Europe with the tube system over the period of 14 years. He also presented measured force coefficients for oscillating airfoils which validated the old flat-plate theory of Theodorsen and the thickness corrections of Kussner (Figures 34 and 35).

In summary the DFVLR/AVA have also become experts in the "Dutch Tube" system and have reached a high stage of automation in the data generating and handling aspects. Their concentration, at least through 1977, had been mostly on interference problems, and they had not yet emphasized transonic unsteady measurements.

C. France

The early French wind tunnel measurements of unsteady pressures on oscillating models[56] grew out of the attempt in 1964 by Destuynder of ONERA to correctthe Theodorsen function C(k) by using measurements of the pitching moment and aileron hinge moment on oscillating airfoils[57]. In addition to using measured unsteady moments, Destuynder referred to unsteady pressure measurements by Molyneux and Ruddlesden in England[57-58]. He used Molyneux's measured pressures at various points on a low aspect ratio wing to adjust C(k). He then found relatively good agreement between theory and experiment over most of the rest of the wing for Mach numbers up to 0.7 and frequencies up to 40 Hz, Figure 36.

In 1970 Destuynder reported on the results of ONERA's installation and operation of the "Dutch Tube" system[59]. They conducted measurements on a wall mounted, low aspect ratio rectangular wing in incompressible flow with pitch amplitudes up to 5° and Reynolds numbers up to 2.7×10^6. Agreement between theory and experiment was excellent for the in-phase component of pressure, particularly away from the wind tunnel wall. However, there was consistent disagreement between theory and experiment - experiment giving the larger values - in the out-of-phase component, Figure 37.

By 1972 ONERA had changed their measurement technique to the use of miniature flush-mounted, "in-situ" transducers for direct measurement of pressures at the model surface. Destuynder[60] reported pressure measurement on a stabilizer oscillating in pitch. Variations were made in pitch amplitude (20', 30', 45'), Mach number (0.4 - 0.85), frequency (30, 40, 50, 58 Hz) and Reynolds number (4-6 x 10). He obtained excellent agreement with theory for the static pressure measurements showing very small thickness

effects. The in-phase components of pressure also agreed for Mach numbers up to 0.6 and reduced frequencies up to 0.75. However, there was consistent <u>over</u>-prediction by theory of the smaller out-of-phase component of pressure. Dat[61] reported similar tests on a trapezoidal half-wing, tested jointly with NLR, Figure 38.

Probably the most extensive ONERA test was reported by Destuynder[62] in 1975 and 1976. They conducted unsteady pressure measurements simultaneously at 140 points on a rigid Mirage F-1 half-wing (with camber and twist removed) with a variety of external stores, Figures 39 and 40. A unique aspect of the test was that a store was tested alone, restrained and excited in pitch by four wires, Figure 41. The store was tested at Mach numbers of 0.4 to 0.9 and at restraint system resonant frequencies of 0, 8 and 14 Hz. The measured unsteady loads on the stores were almost negligible for reduced frequencies (based on diameter) up to 0.2).

When mounted under the oscillating wing surface, the stores continued to experience relatively small aerodynamic loads, not much different from their loads in the wire-restrained test. However, there were large differences in the unsteady wing loads attributed to the presence of the stores, particularly on the lower surface, Figure 42. One of Destuynder's most important conclusions was that it was obviously important to include the unsteady aerodynamic effects of the stores on the wing in flutter calculations. It was no longer sufficient to consider only store inertias and stiffnesses.

Recently Grenon and Thers[63] of ONERA have reported a series of subsonic and transonic unsteady pressure measurements on a supercritical, two-dimensional airfoil with a 25% chord oscillating flap. They used 78 static pressure taps and 32 dynamic transducers (16 on each surface) for unsteady tests. They were able to conduct parametric variations of frequency, airfoil

incidence, flap incidence, and flap oscillatory amplitude. The effects of shock/boundary layer interaction were shown to be very prominent, Figures 43-45.

In summary, after early attempts to use the "Dutch Tube" system, ONERA recently has stressed the use of large numbers of miniature, flush-mounted "in situ" pressure transducers. While each channel of instrumentation is relatively more expensive, they have developed a systematic, productive measurement system which meets their needs.

D. United Kingdom

At about the same time that Bergh was developing the "Dutch Tube" measurement system, Molyneux and Ruddlesden[64,65] of the RAE were developing an early version of the "in situ" strain-gage pressure transducer. The transducers were mounted in a wing midplane to measure differential pressures between the upper and lower surfaces. They oscillated rectangular wings of aspect ratios 2.47, 3.3 and 3.7 in pitch about various axes for reduced frequencies up to 0.25. Comparison with the theories of the time was not good.

With some redesign of the transducers, the Molyneux system was applied by Keating[66] to slender wings in heave about high incidence and by Ruddlesden[67] et al in a flexible chordwise bending mode as late as 1967. The coverage of transducers was not particularly fine (Figure 46) and a great deal of precision in the pressure measurements was not possible (Figure 47). Ruddlesden cited many experimental problems with calibration of the transducers, tunnel turbulence, phase drift, small signal-to-noise ratio, changing tunnel ambient conditions, and wear in the model drive system. Still, they felt that they had obtained decent correlation with theory, except near the apex of the slender wing.

With few exceptions[68], interest in wind tunnel pressure measurements on

oscillating models seemed to have waned temporarily in the United Kingdom. Great emphasis was placed on force and moment measurements on oscillating models and the assessment of wind tunnel interference effects. Literally dozens of publications ensued (See NASA Langley Working Paper LWP-695 by E. C. Yates for a survey of those measurements through 1968).

In 1976 C. G. Lodge[69] of the British Aircraft Corporation arranged a series of supersonic unsteady pressure measurements on a rigid wing with an oscillating control surface (Figure 48). The model was actually designed, built and tested at the NLR in the Netherlands, using the improved calibration procedures for the "Dutch Tube" system. Agreement between the measured pressures near the oscillating control surface and calculations by Lodge and by Schmid of MBB (Germany) was at best, fair (Figure 49).

Within the last few years interest has rekindled in unsteady pressure measurements in the UK[70,71], and there is indication of unsteady pressure measurements on a transport-type wing with supercritical airfoil sections[72], Figures 50 and 51, as well as several other research-type wings.

E. NORA

"NORA" is an acronym for a cooperative testing program by NLR of the Netherlands, ONERA of France, RAE of the United Kingdom, and AVA of the Federal Republic of Germany. The program consists of unsteady pressure measurements in each of the four countries on an oscillating model of the Mirage F-1 taileron, Figure 52. Pressures have been measured along three chordwise sections and the results presented to AGARD in 1979 by N. Lambourne of the RAE. Publication is still pending[73] as an AGARD report.

SECTION III

CONCLUDING REMARKS

European unsteady aerodynamic testing has been dominated by the names of Bergh and Tijdeman of the Netherlands, Destuynder of France, Forsching of Germany and Lambourne of the United Kingdom. Most of these scientists work in laboratories that are partially funded by the national governments and partially dependent on industrial sources. They have developed and applied two test techniques. The "tube" system and the "in situ" transducer system. They have thoroughly tested a series of test configurations such as conventional airfoils, airfoils with flaps, clean three-dimensional wings, all-moveable tails, wings with stores, T-tails, wing-tail combinations, wing-engine combinations, and supercritical wings. As a result, there is a great opportunity in the European research centers for an understanding of the physics of unsteady aerodynamic flows and an early assessment of the effects on aircraft design problems of dynamic loads, stability, and flutter.

In the United States, however, the facilities to support unsteady aerodynamic testing are controlled by exclusively industrial or exclusively governmental agencies, and competition for test time, funding and management attention is intense. Clear economical reasons have not been presented to justify the investigations necessary to doggedly pursue the development of the necessary technology. Therefore, the major airframe companies have not realized the benefits and have not pushed for the development of the testing techniques. It is difficult to determine if the absence of this well-developed technology has hurt the United States position in the manufacture of commercial and military aircraft. Certainly the US practice of exclusive use of aeroelastic models for flutter testing has had an excellent record of aircraft

flight safety. However, flutter models give only an indirect view of the physics of unsteady aerodynamic flows. Investigations of Reynolds number effects, wall effects, oscillating shocks, shock-boundary layer interaction, and control surface buzz will require greater physical understanding as will experiments used to guide the development of prediction methods.

At this point new U.S. research facilities for unsteady pressure measurements on two-dimensional airfoils are operating at NASA Ames, and NASA Langley is developing a facility for testing three-dimensional wings. These facilities should blend exploratory investigations for simple configurations to understand the physics of transonic unsteady aerodynamic flows with more applied investigations for practical aircraft wings. Whether or not the development of a United States "production" testing capability, similar to that of NLR in the Netherlands, is advisable will depend on the future importance of aeroelastic phenomena, continued access to European test results, and significant payoffs that would justify the investments.

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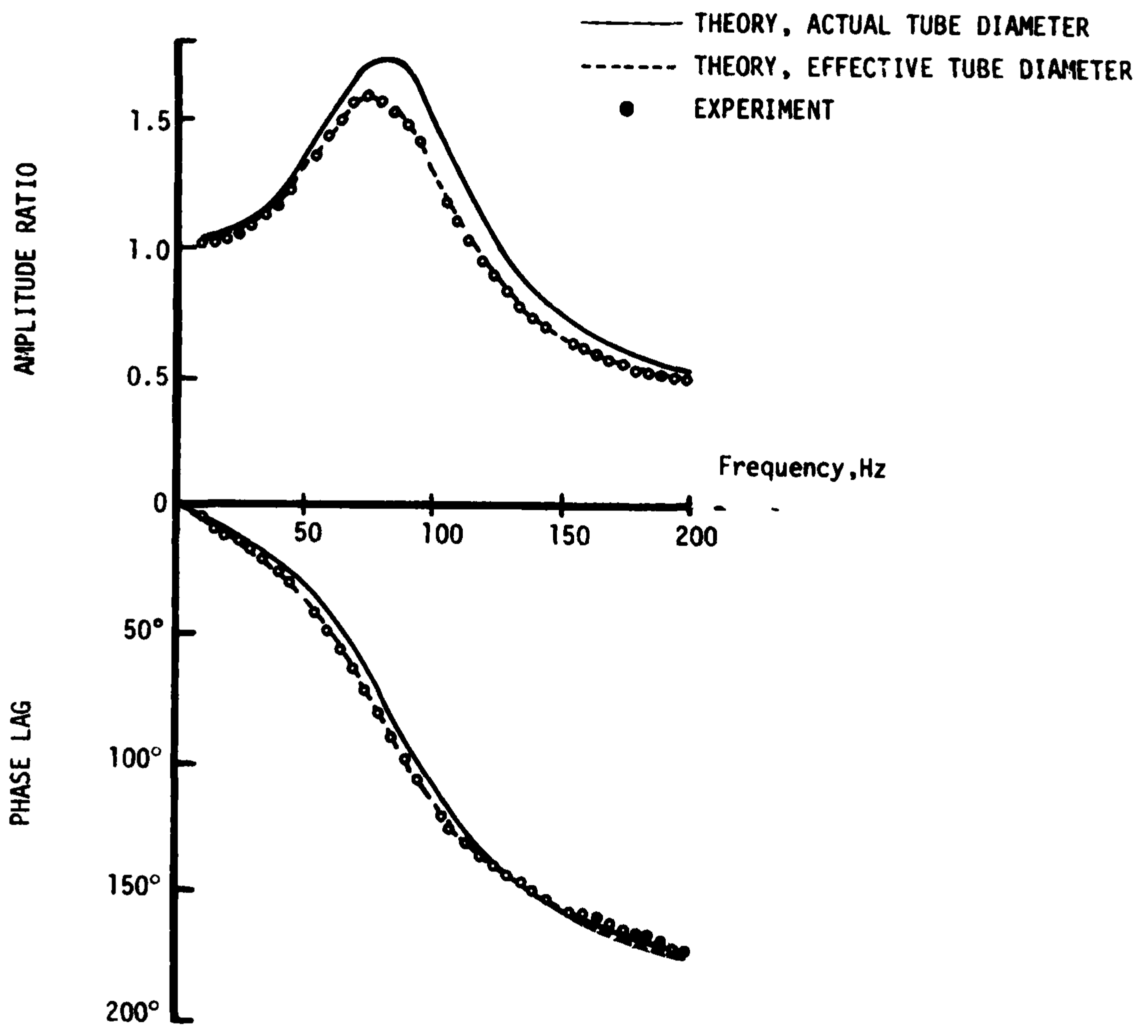


Figure 1 Experimental and Theoretical Results for a Single Pressure Measuring System

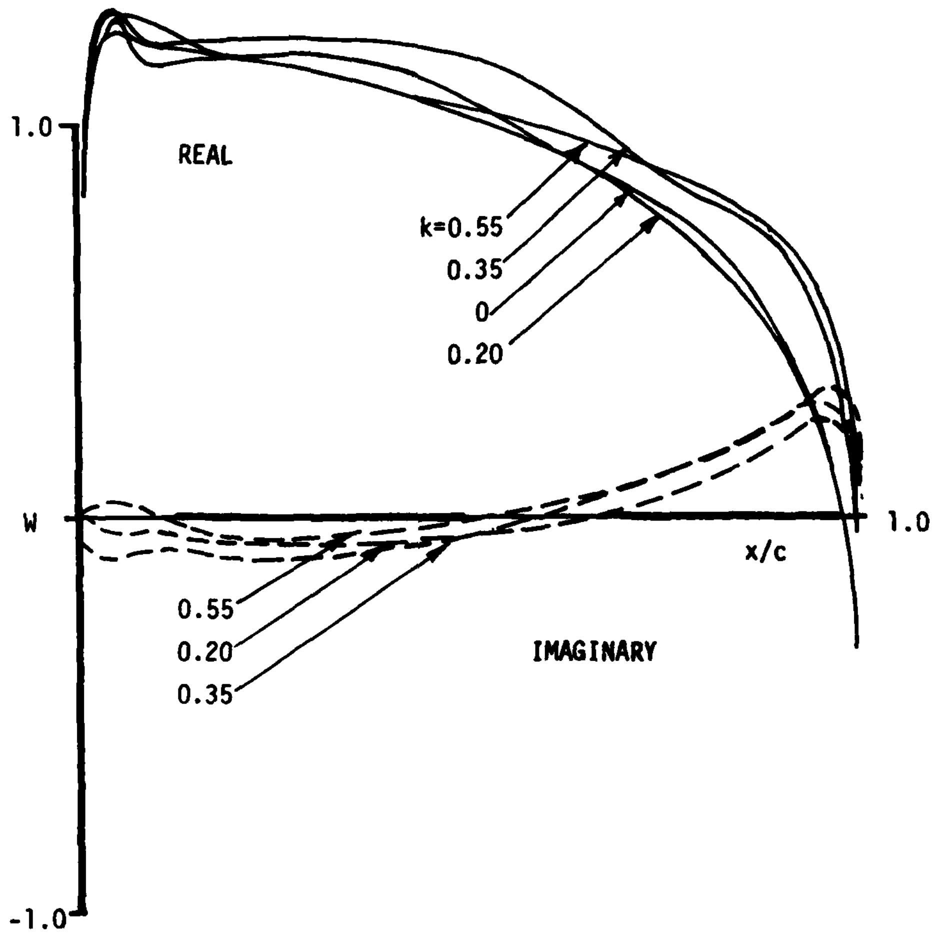


Figure 2 Pressure Correction Matrices for Stabilizer with Tip

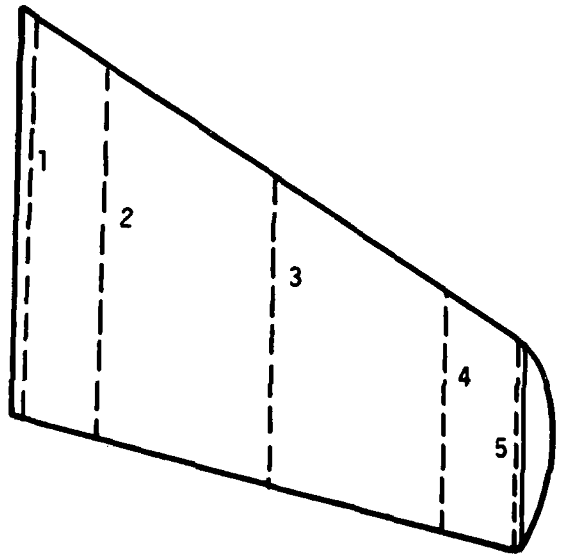


Figure 3 Stabilizer Planform

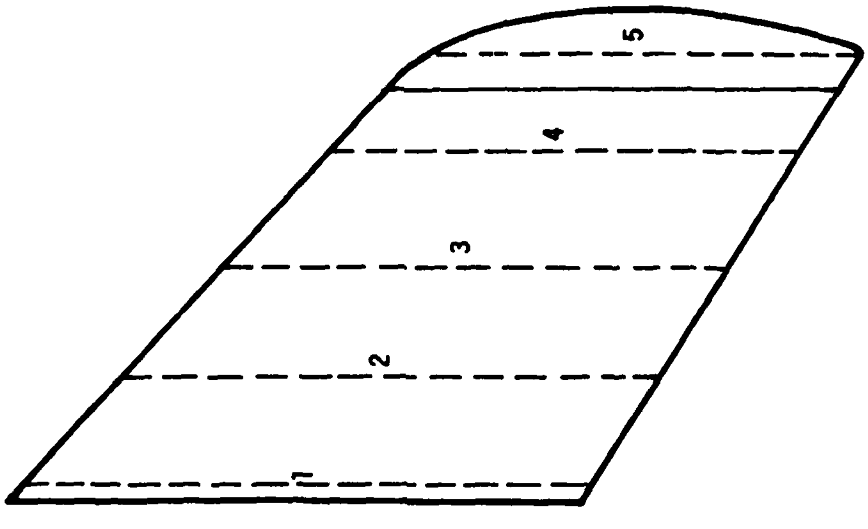


Figure 4 Fin Planform

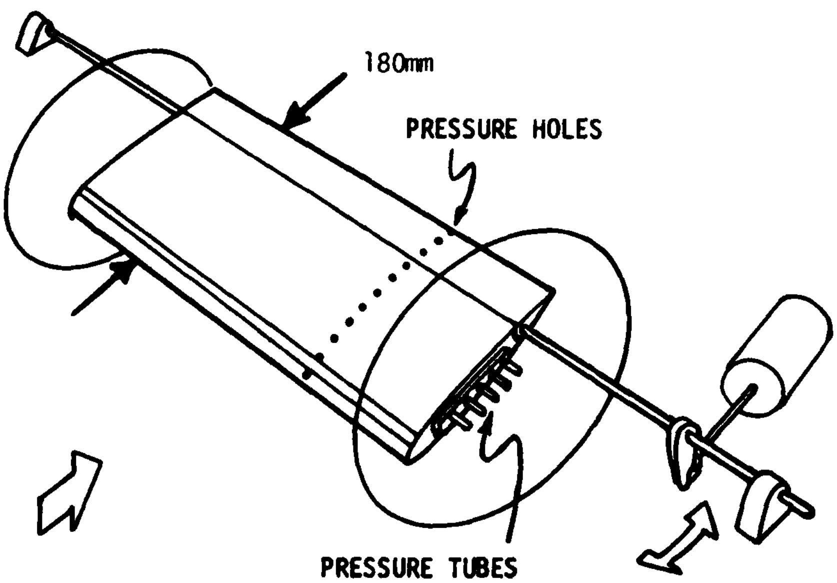


Figure 5 Test Set Up in the NLR Pilot Wind Tunnel

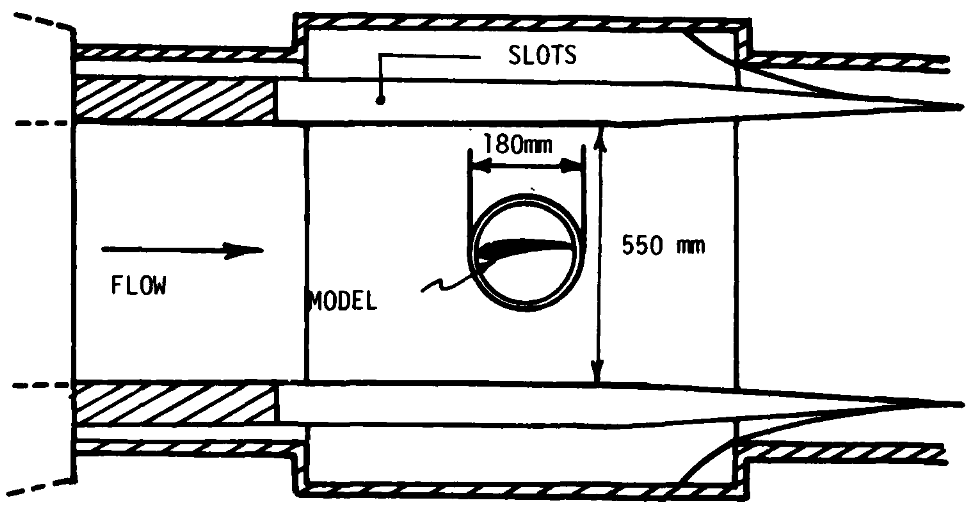


Figure 6 Transonic Test Section of the Pilot Tunnel

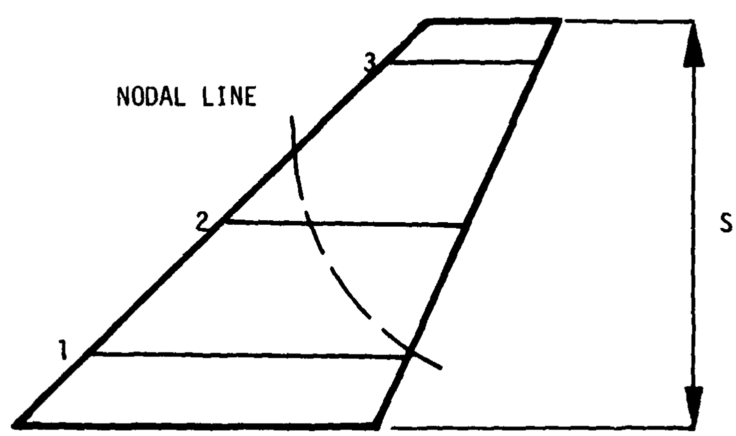


Figure 7 Swept Wing Oscillating in an Elastic Mode

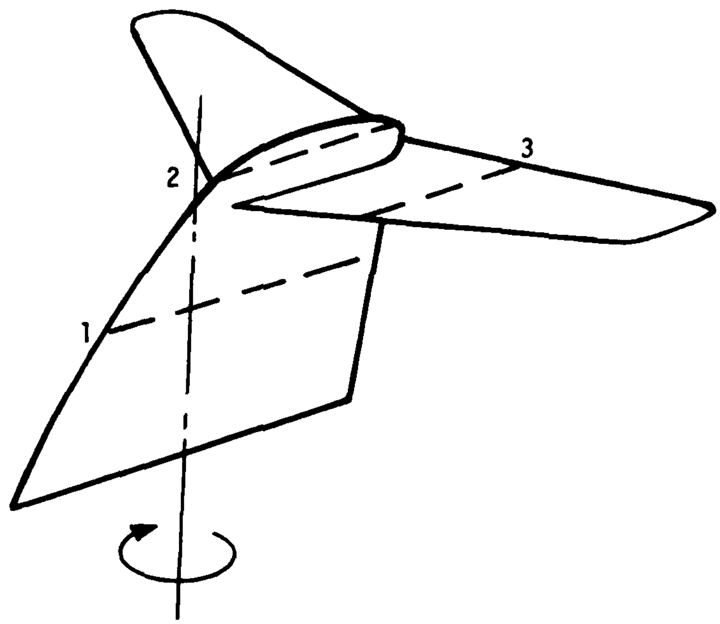


Figure 8 Yawing T-Tail

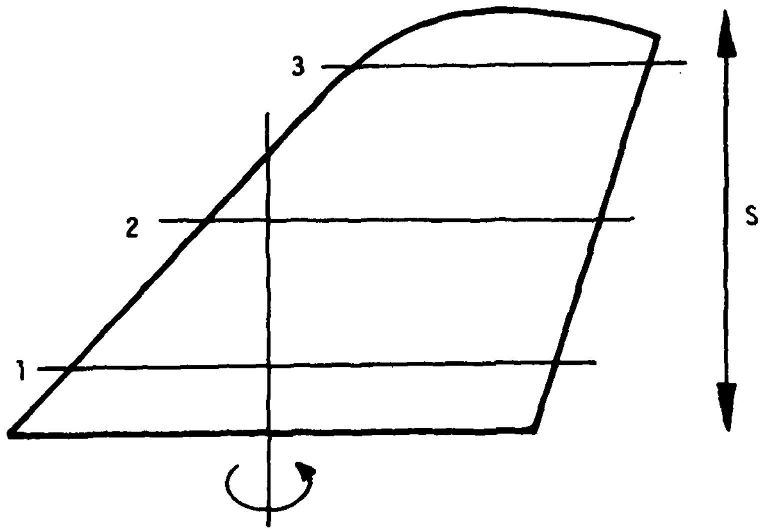


Figure 9 Half-Wing Used to Measure Wall Effects

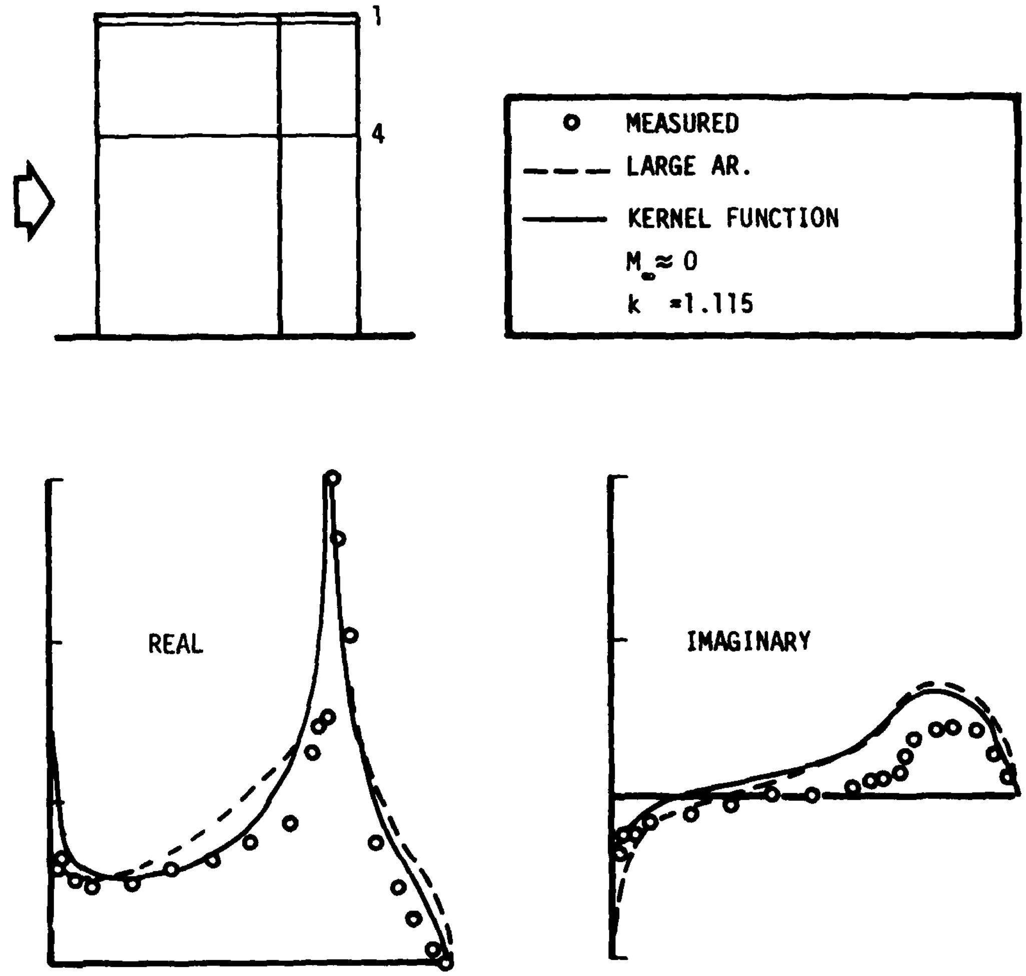


Figure 10 Unsteady Pressure Distributions on Section 4 of a Rectangular Wing with Full Span Control Surface

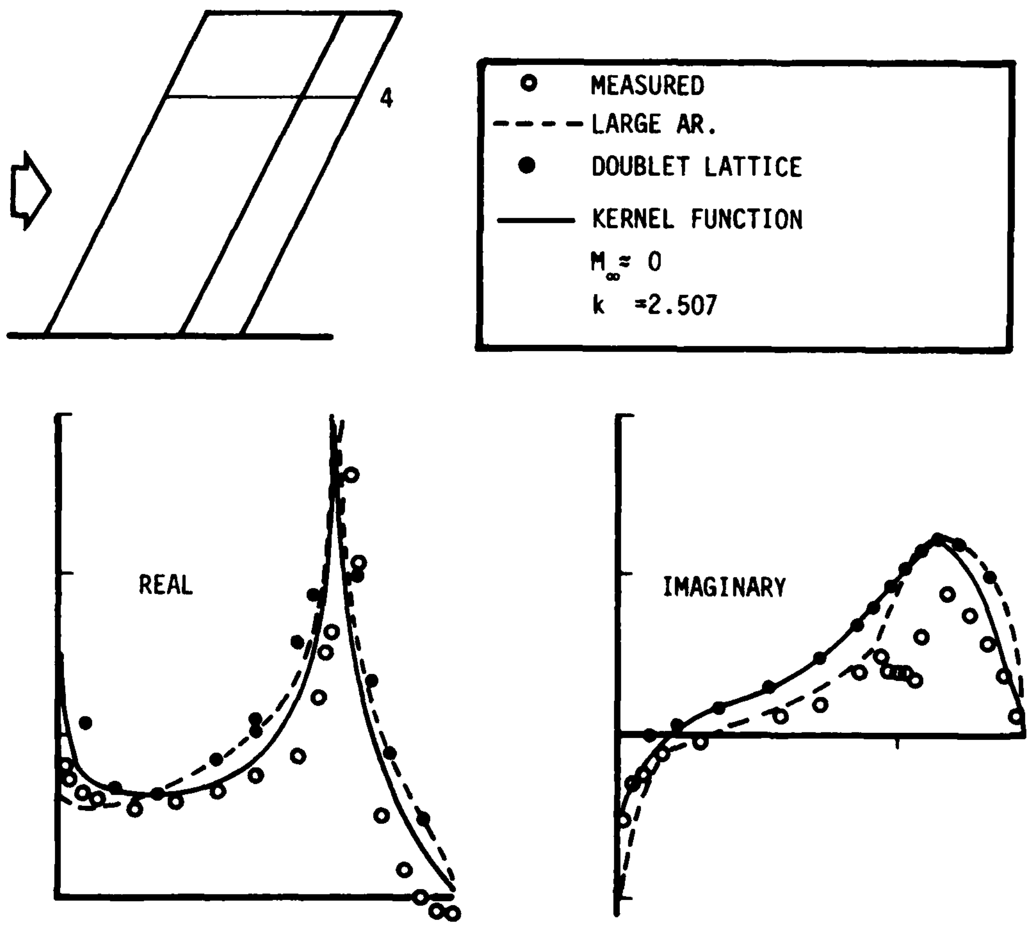


Figure 11 Unsteady Pressure Distributions on Section 4 of a Swept Wing with Full Span Control Surface

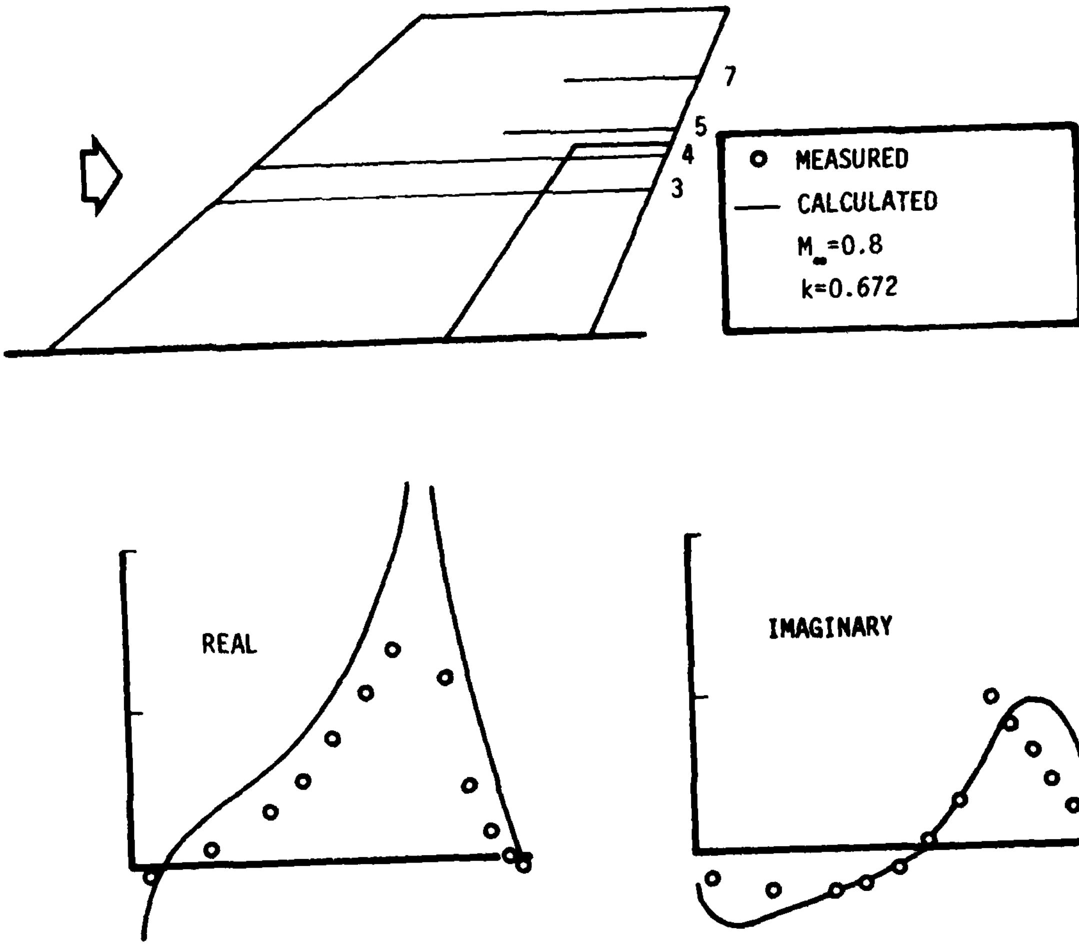


Figure 12 Unsteady Pressure Distribution on Section 3 of a Swept Tapered Wing with Inboard Control Surface

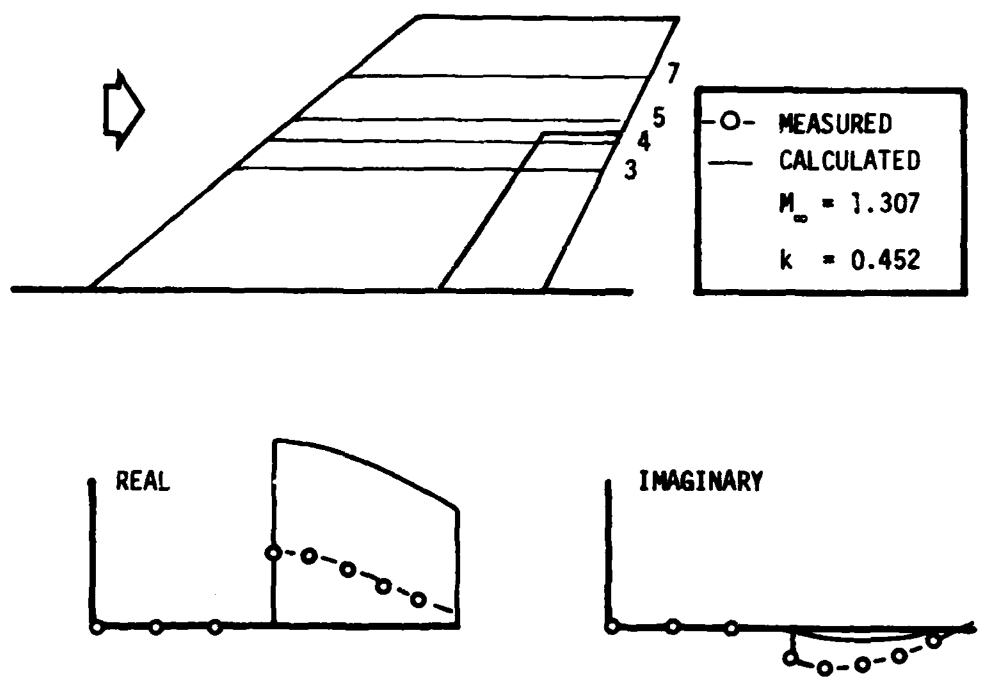
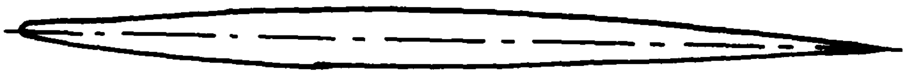
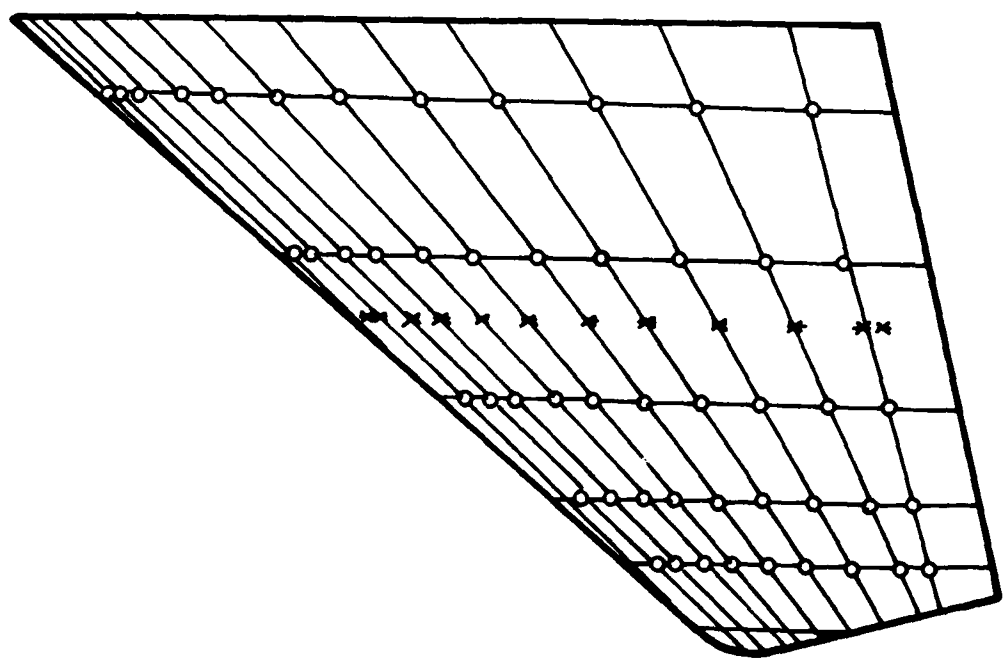


Figure 13 Unsteady Pressure Distributions on Section 3 of a Swept Tapered Wing with Inboard Control Surface

AIRFOIL CROSS SECTION





O PRESSURE ORIFICES
✱ IN SITU TRANSDUCERS

Figure 14 Planform of the Model and Location of the Pressure Orifices and the In Situ Transducers

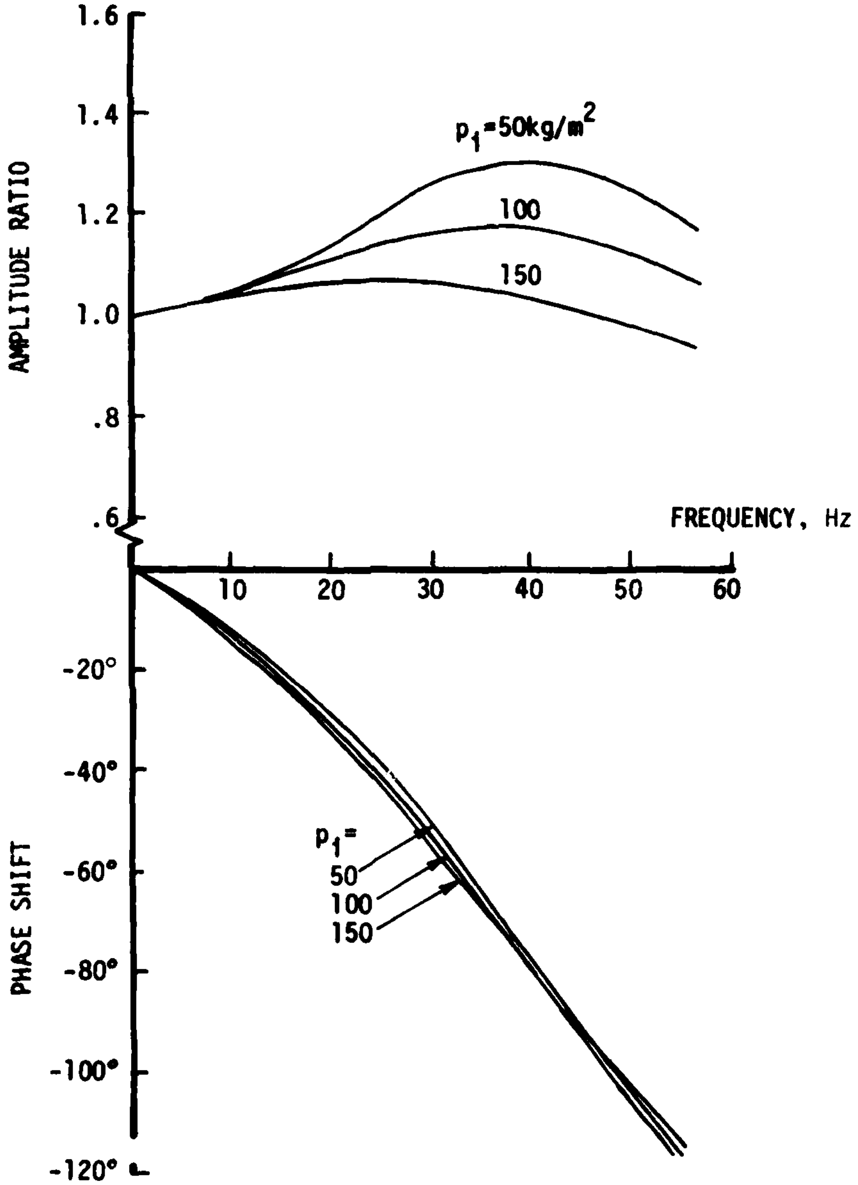


Figure 15 Frequency Response of the Short Tube System for Various Levels of the Oscillatory Input Pressure

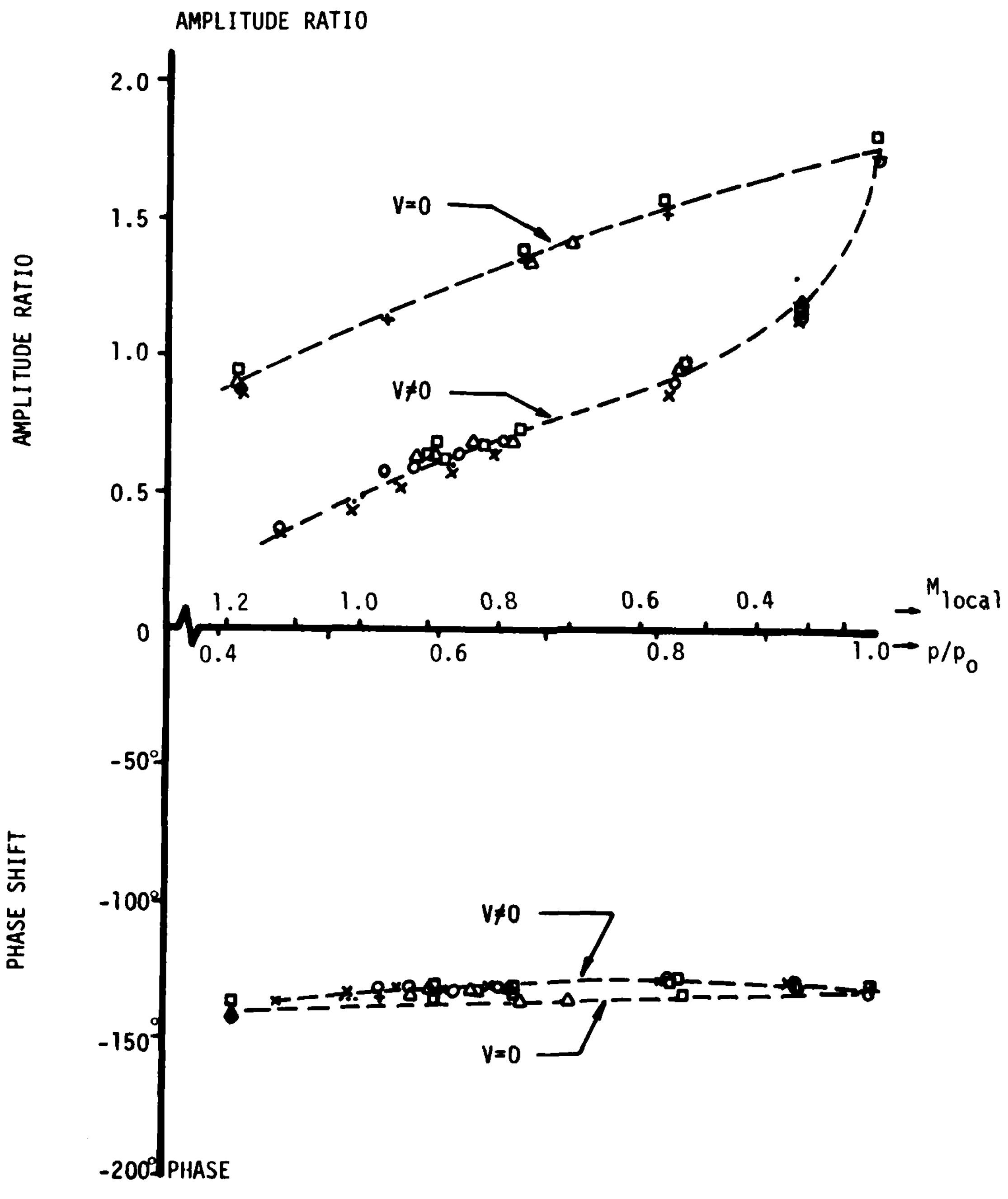


Figure 16 Measured Transfer Functions in Still Air and with Wind

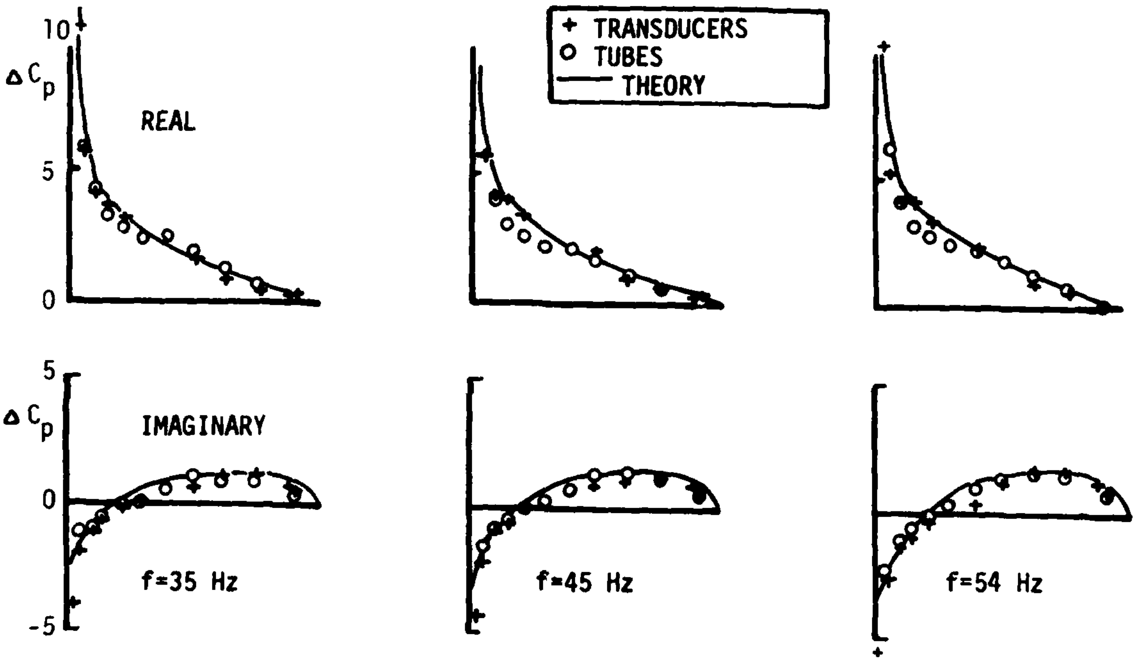


Figure 17 Unsteady Pressure Measured with In Situ Transducers and Via Tubes

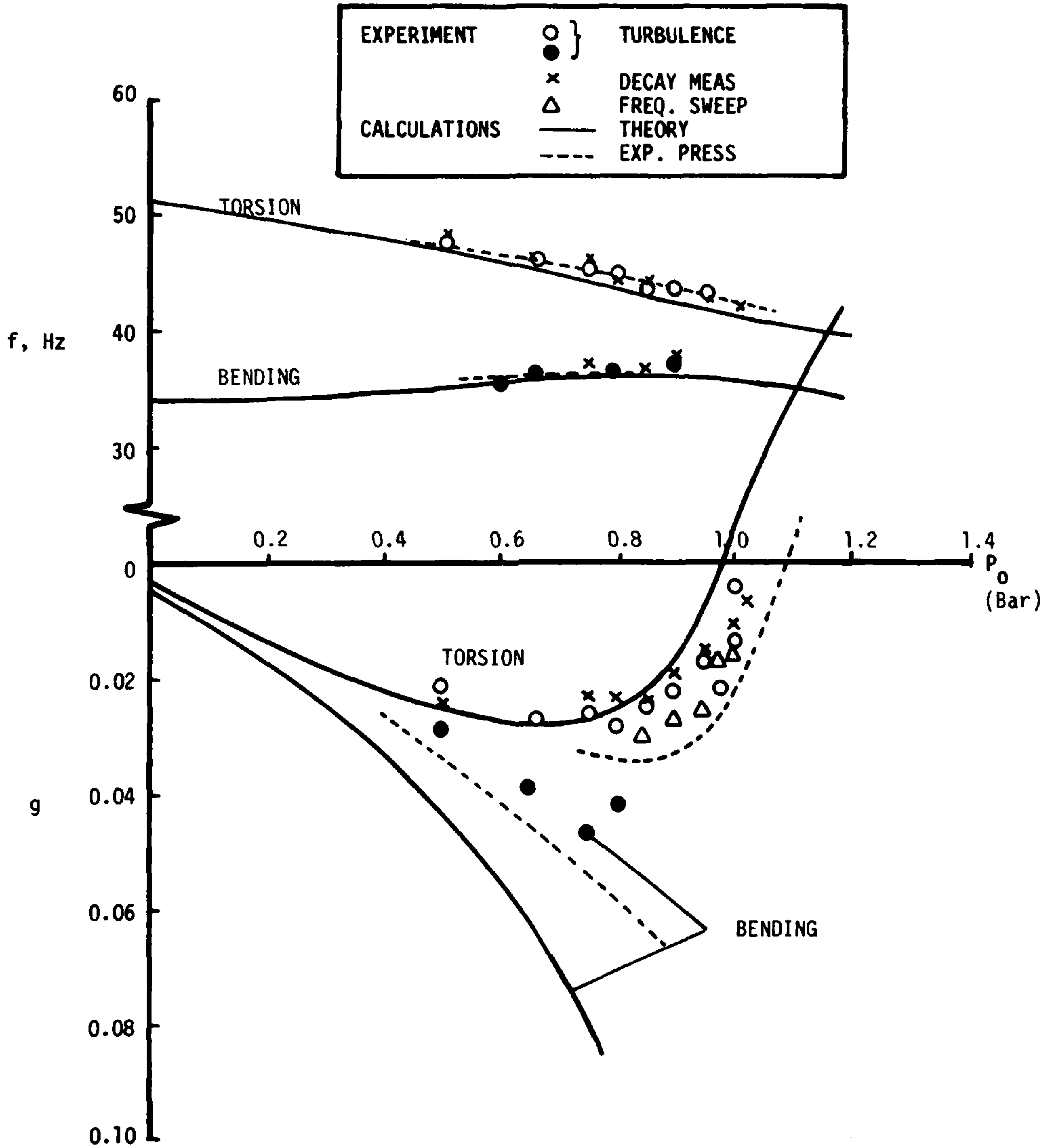


Figure 18 Flutter at M_∞=0.8

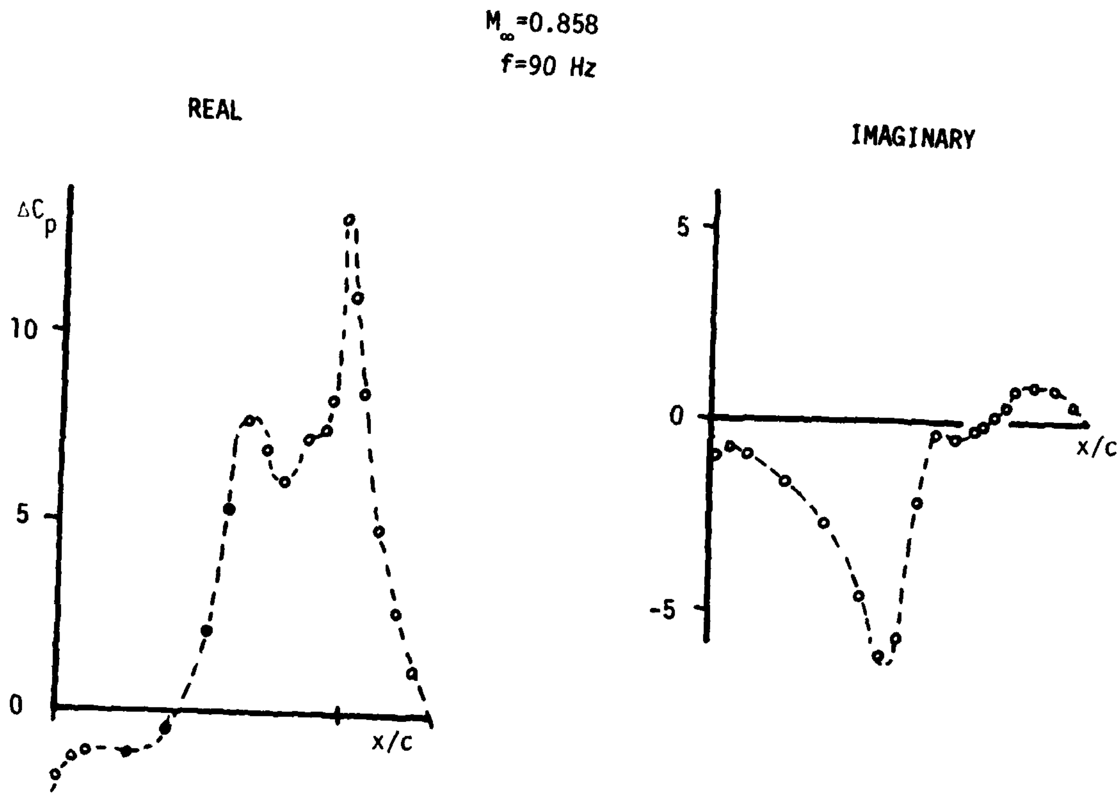


Figure 19 Unsteady Pressure with Oscillating Flap

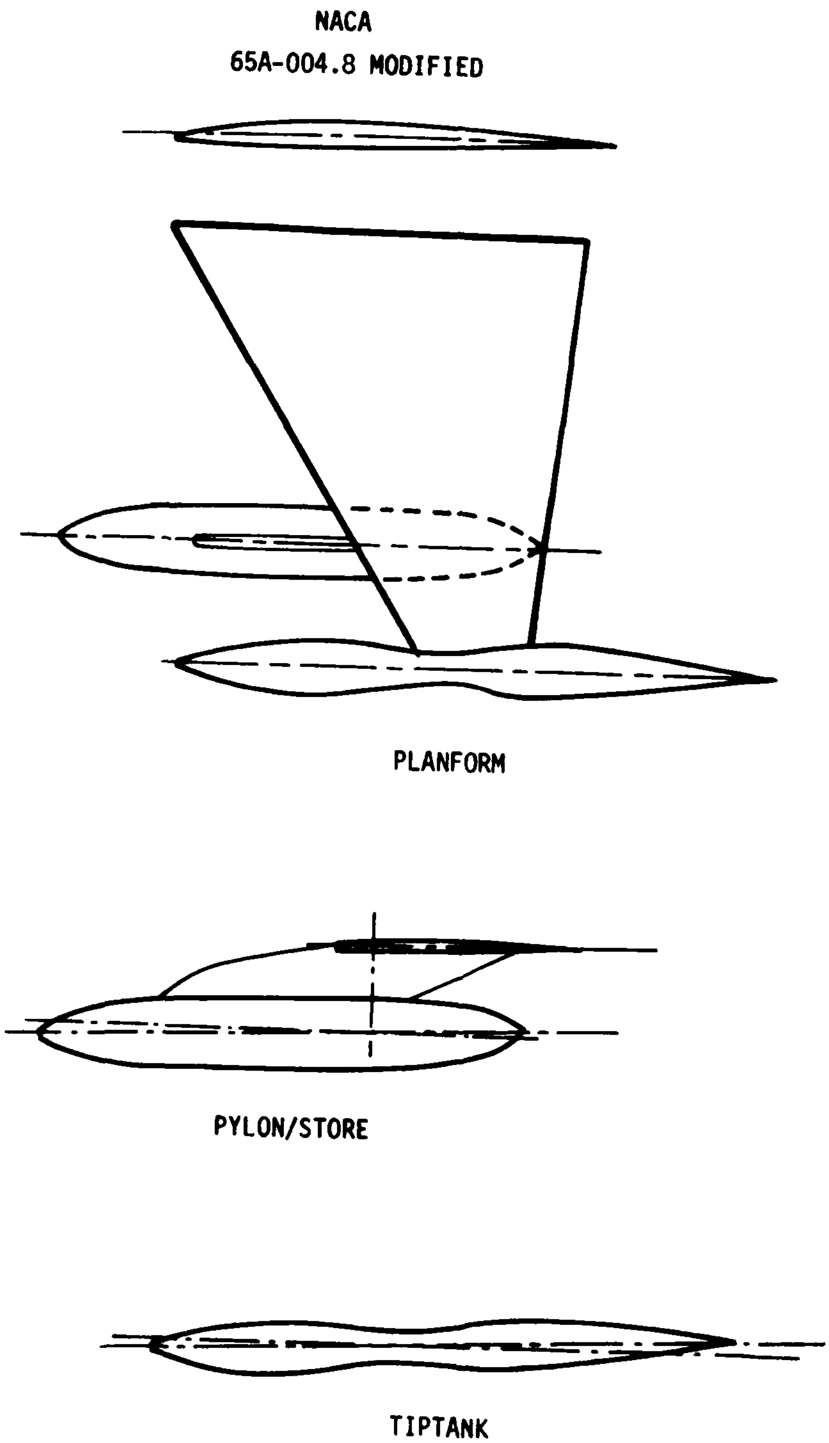
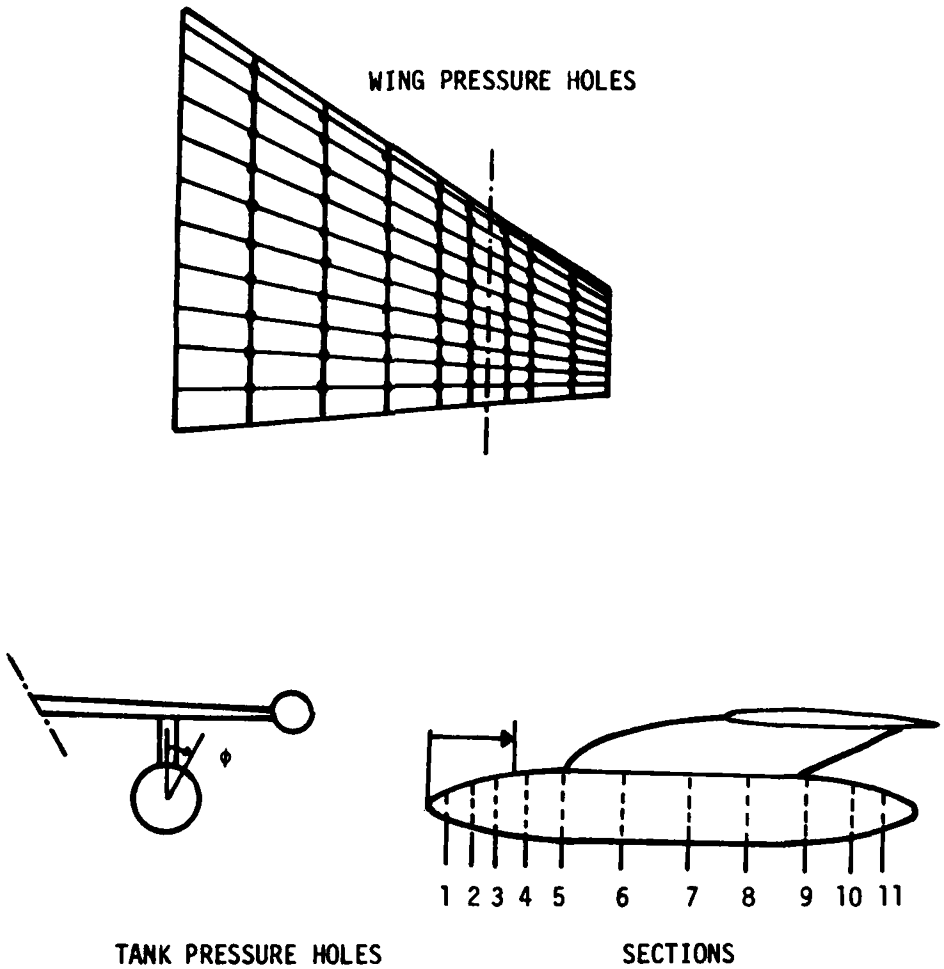


Figure 20 Wing with Stores



φ (°)
0
30
90
150
180
210
270
330

Figure 21 Wing and Store Pressure Orifices

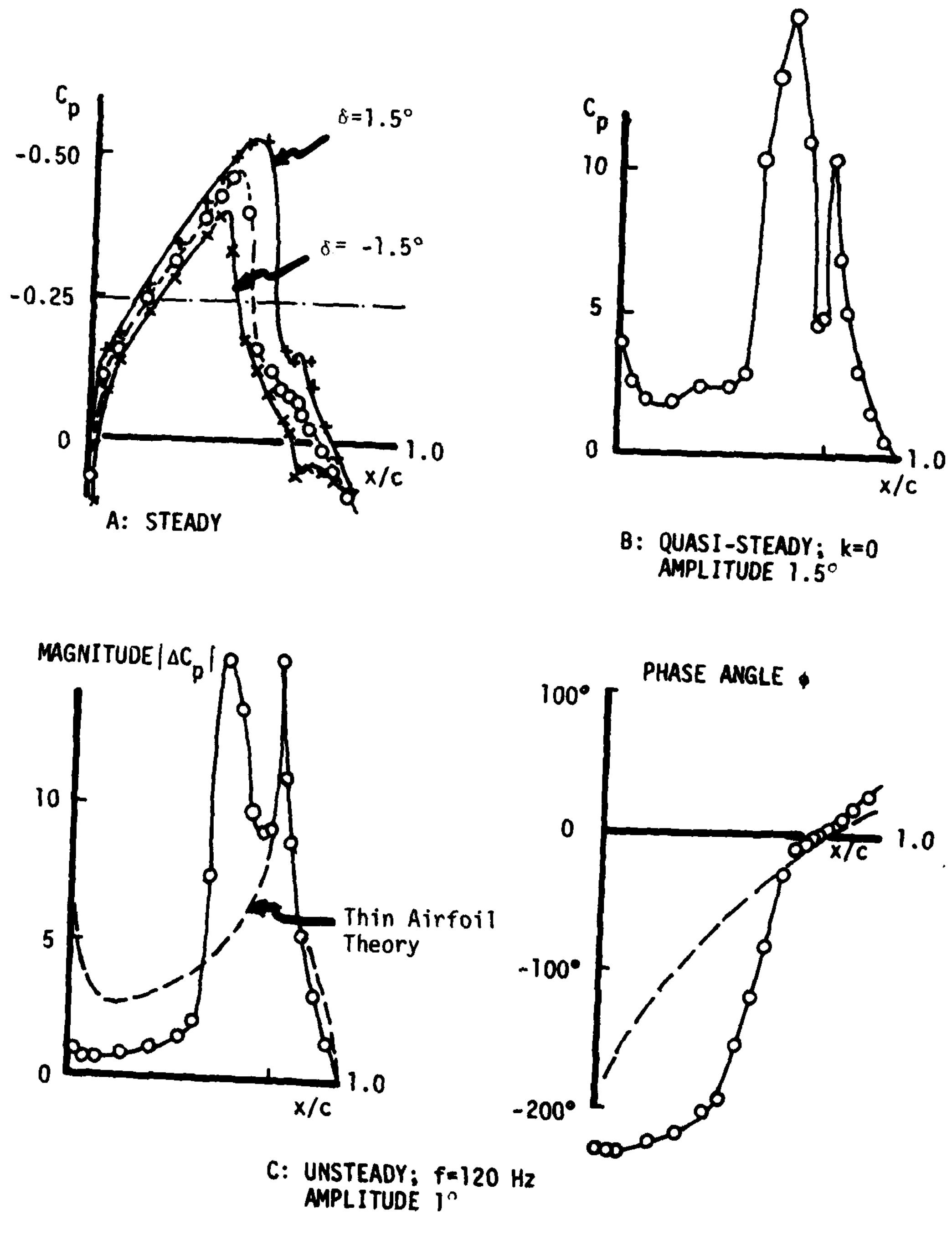


Figure 22 Steady, Quasi-Steady and Unsteady Pressure Distributions in Transonic Flow on a NACA 64A006 Airfoil with Flap, M_∞=0.875

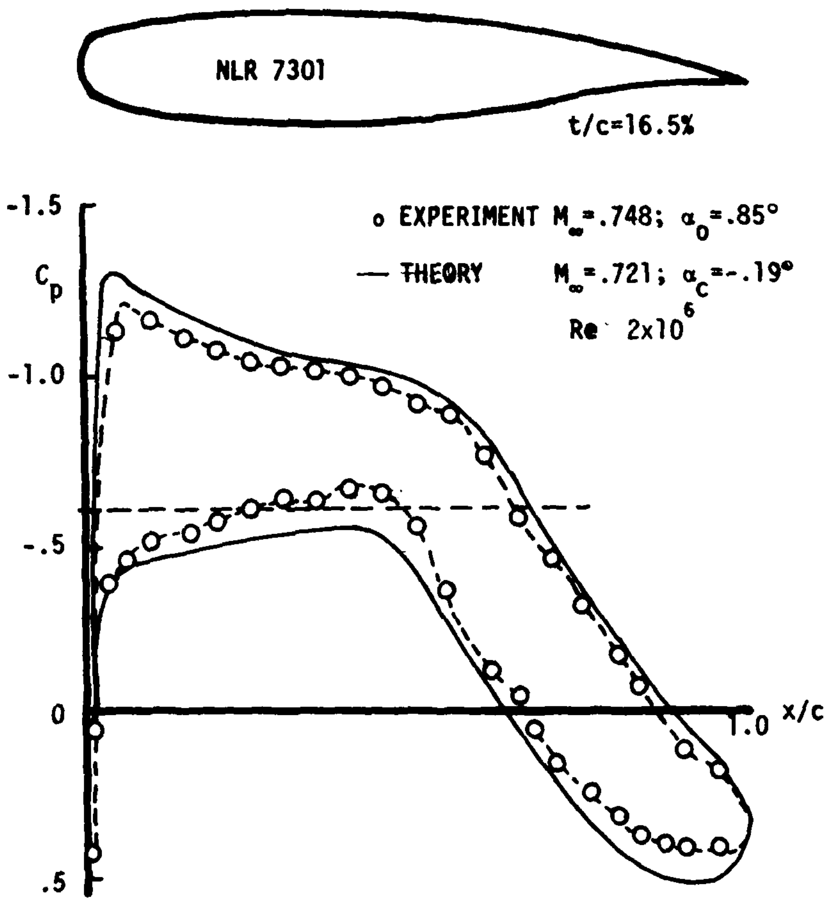


Figure 23 Steady Pressure Distribution at the "Shock Free" Design Condition

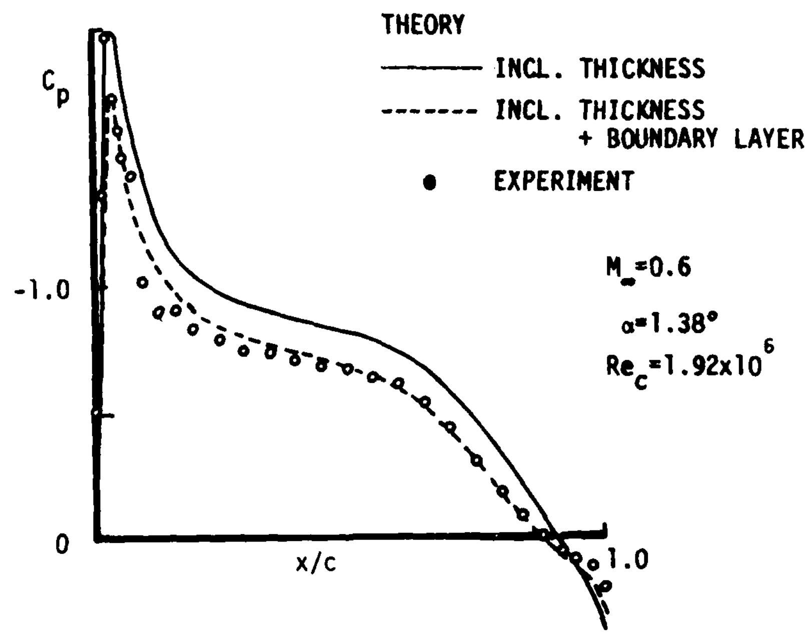


Figure 24 Steady Pressure on the Upper Surface of an NLR 7301 Airfoil

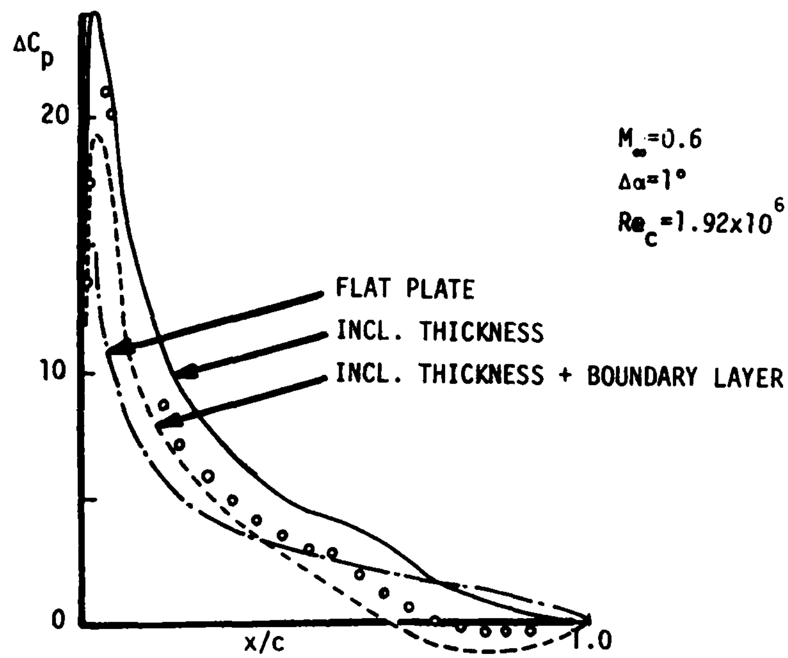
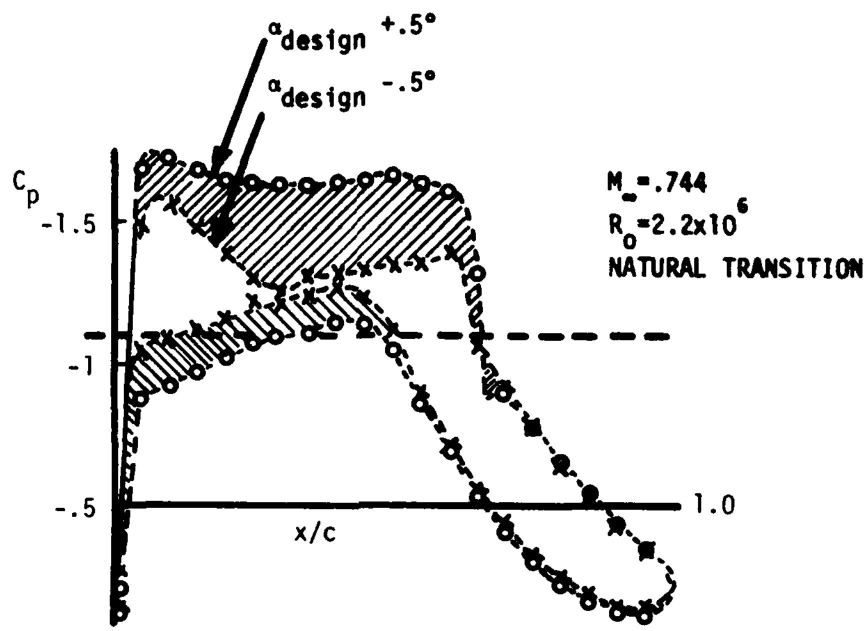


Figure 25 Quasi-Steady Pressure Distribution for a Pitching NLR 7301 Airfoil



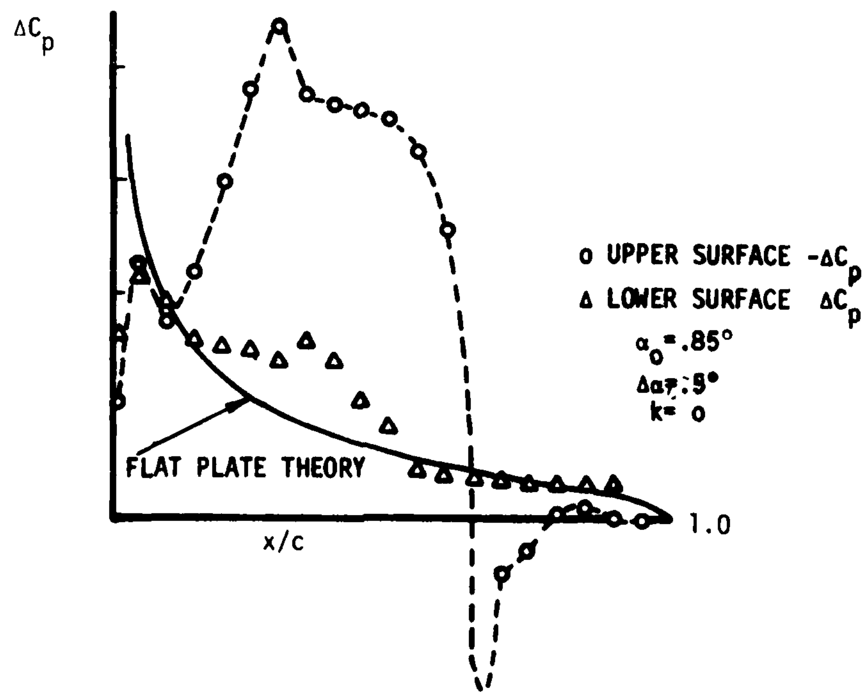


Figure 26 Steady and Quasi-Steady Pressure Distributions on NLR 7301 Airfoil Around the Design Point

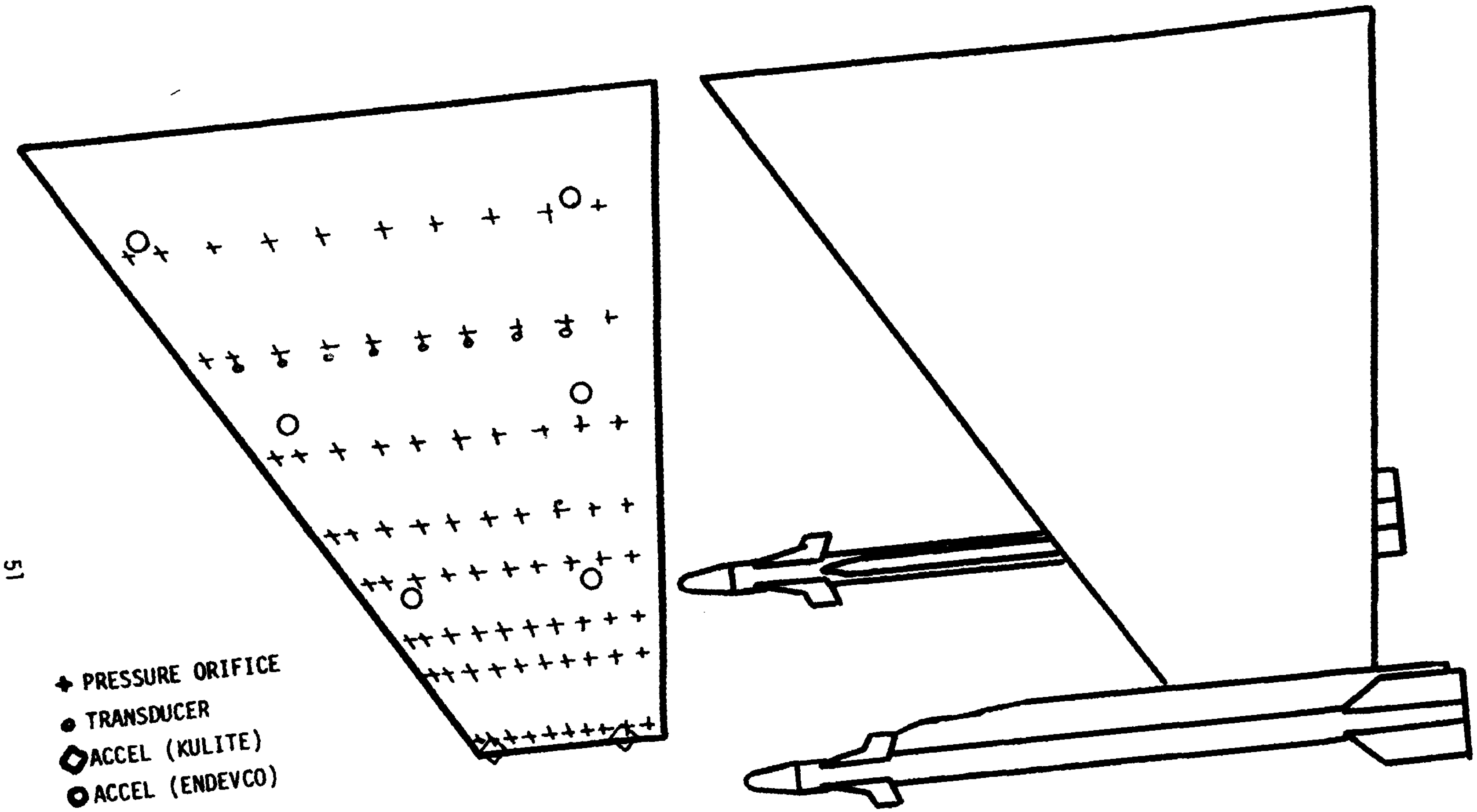


Figure 27 NF-5 Wing with External Stores

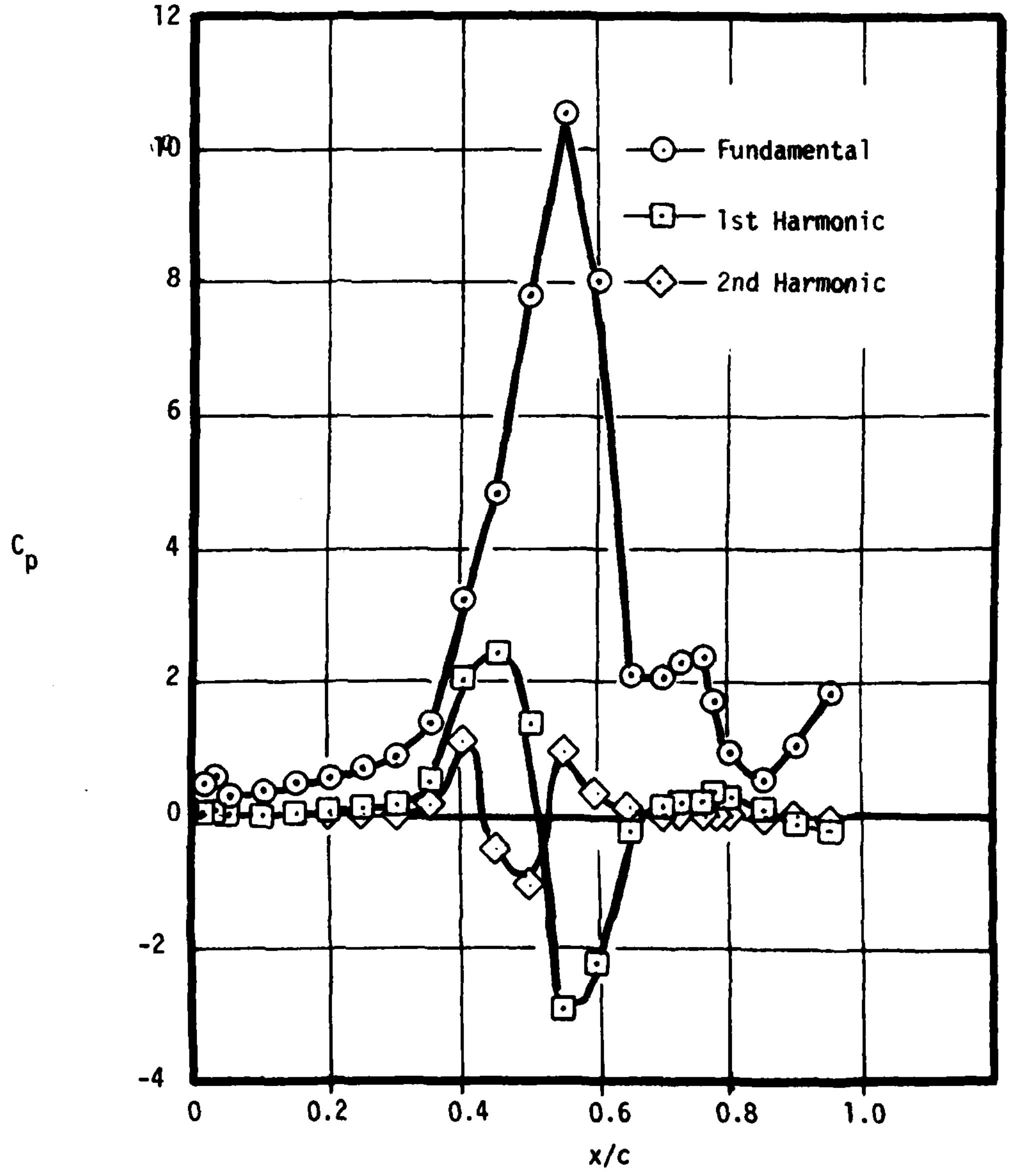


FIGURE 28 Real Part of the Upper Surface Pressure on a NLR 7301 Airfoil with Oscillating Flap. M_∞=0.755, ω=30Hz, k=0.067

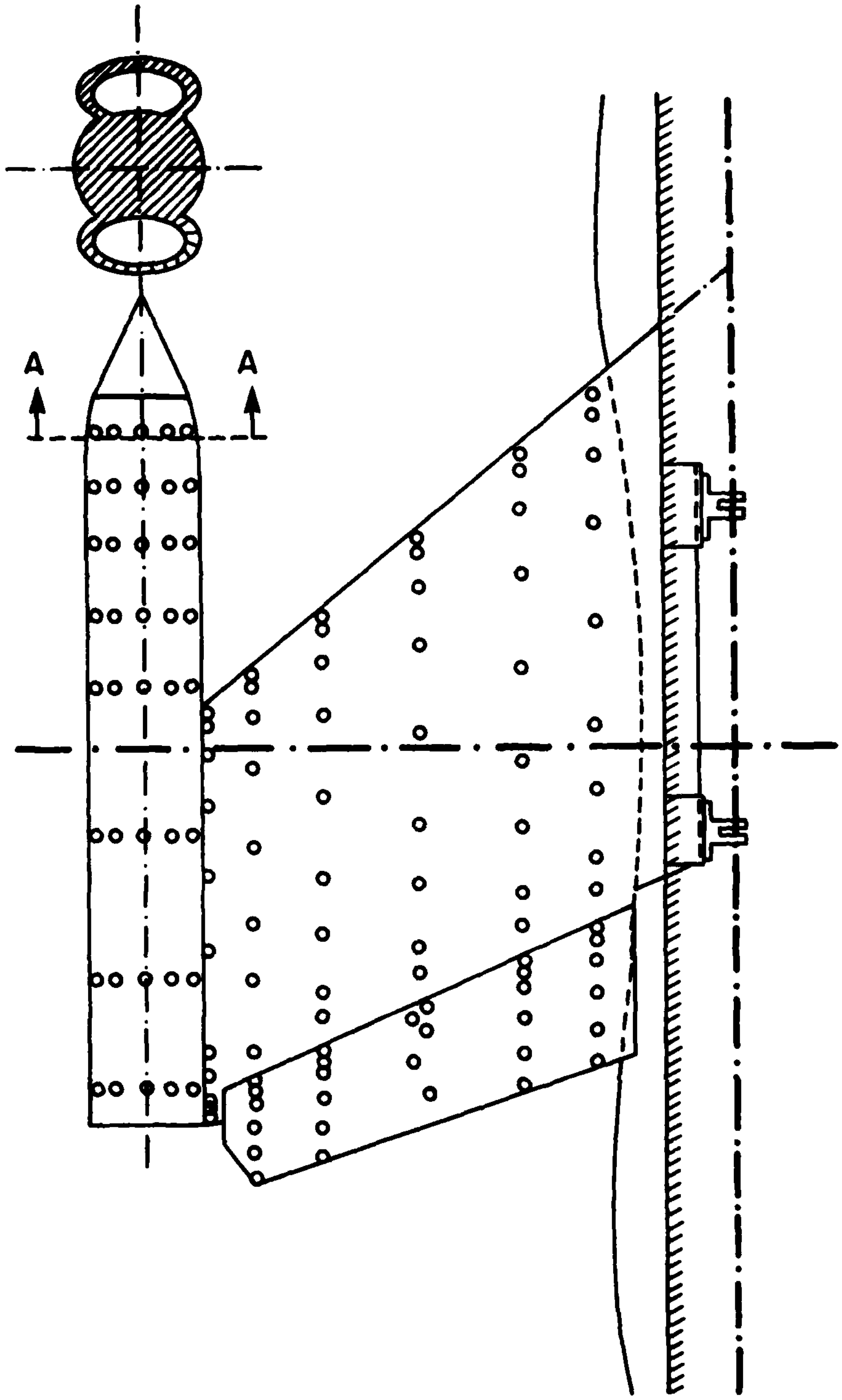


Figure 29 Aspect Ratio 1.45 Wing with Wing-Tip Engine Simulation

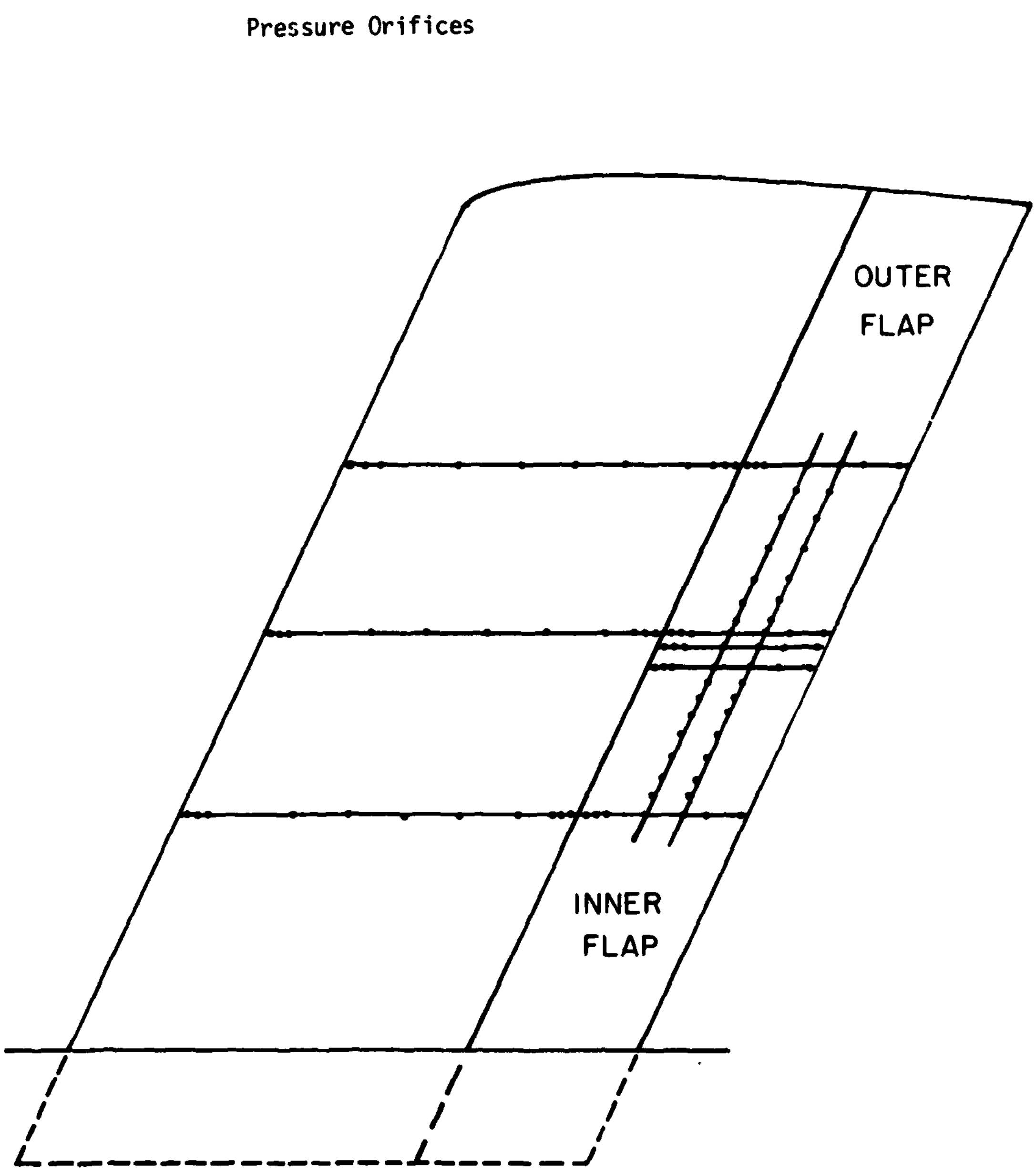


Figure 30 DFVLR Model to Investigate Control Surface Singularities

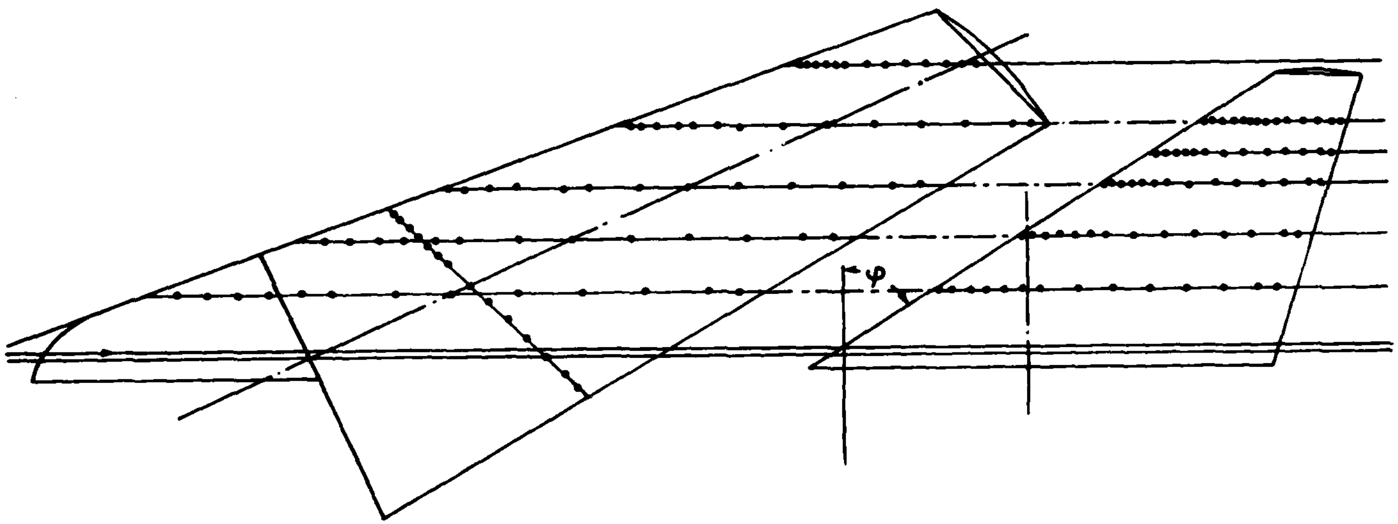


Figure 31 DFVLR Variable-Sweep Wing with Movable Stabilizer

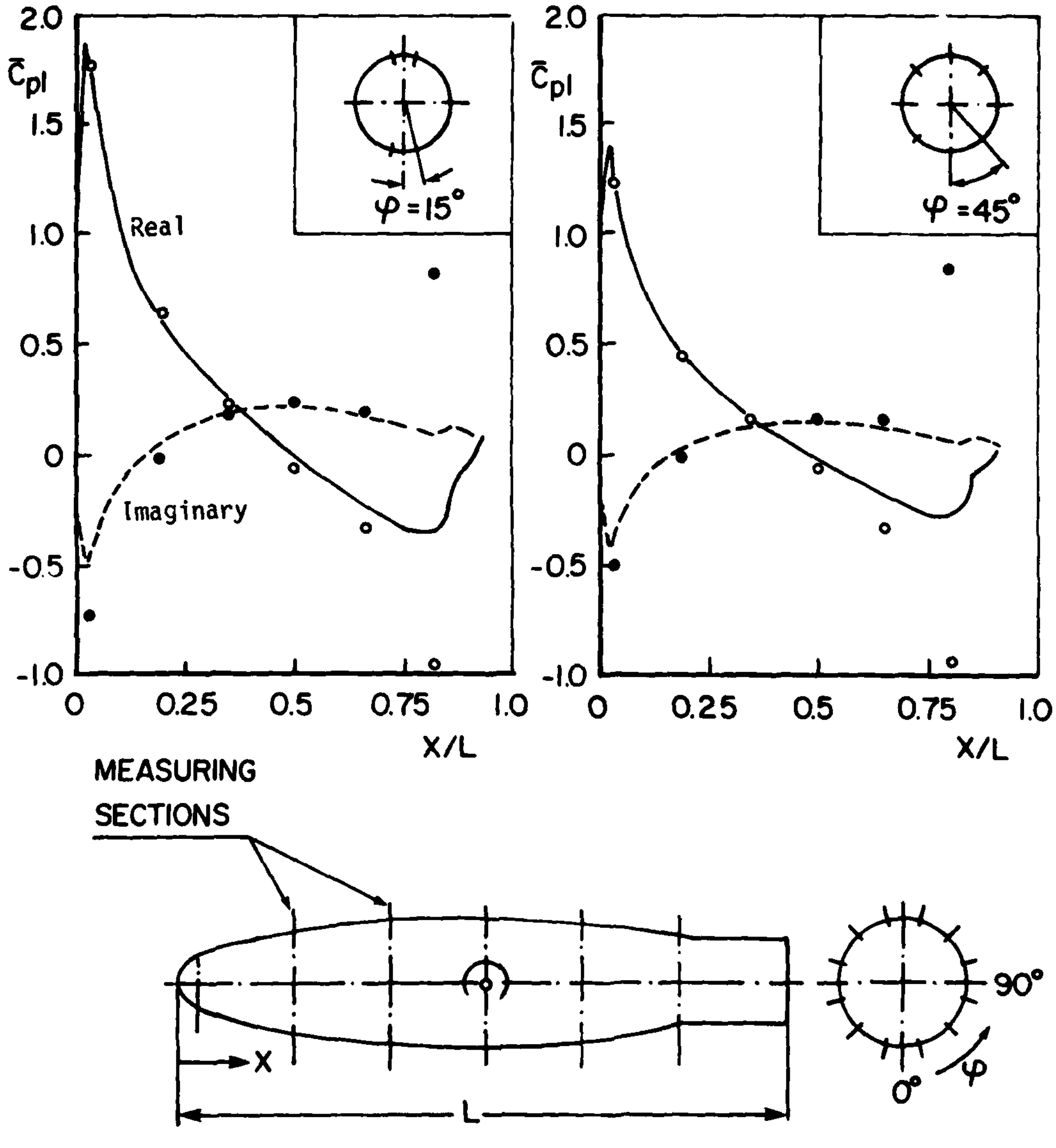


Figure 32 Body of Revolution Oscillating in Pitch

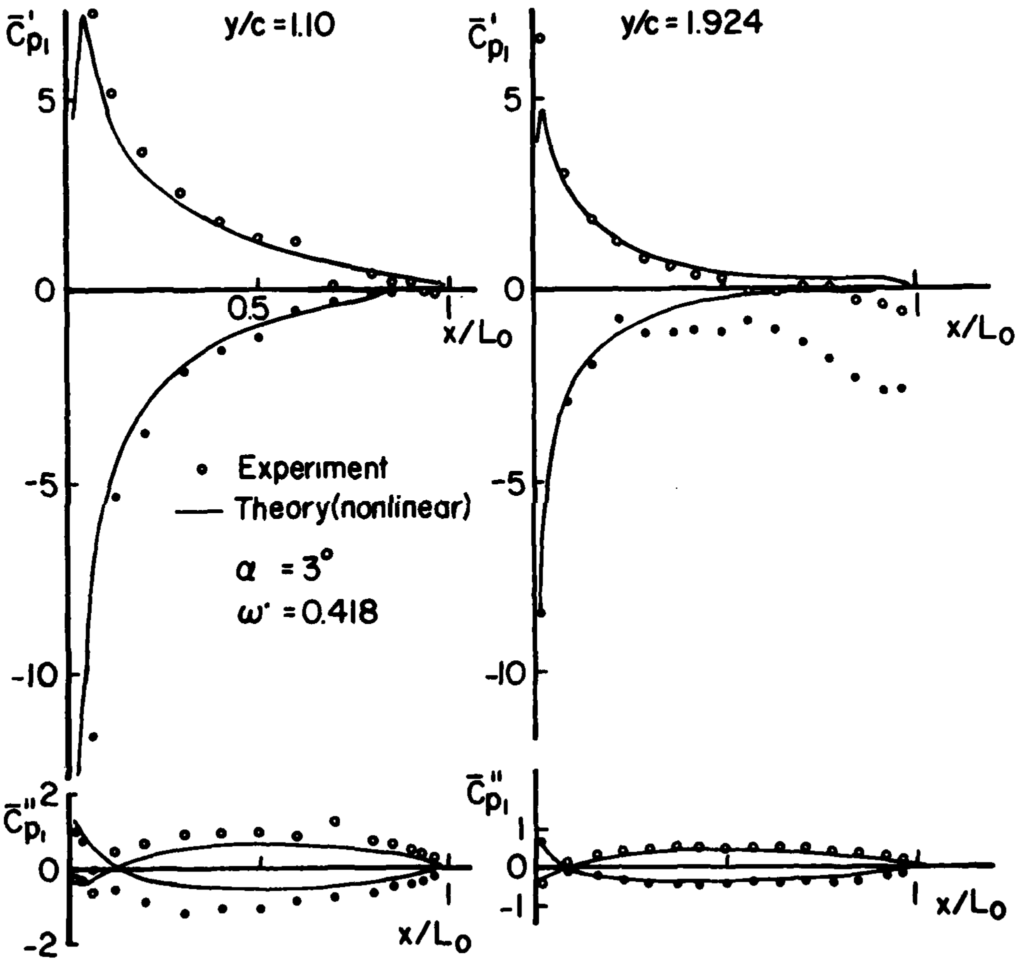


Figure 33 Aspect Ratio 4 Rectangular Wing with NACA 0012 Airfoil Section Pitching About an Initial Incidence of 3°

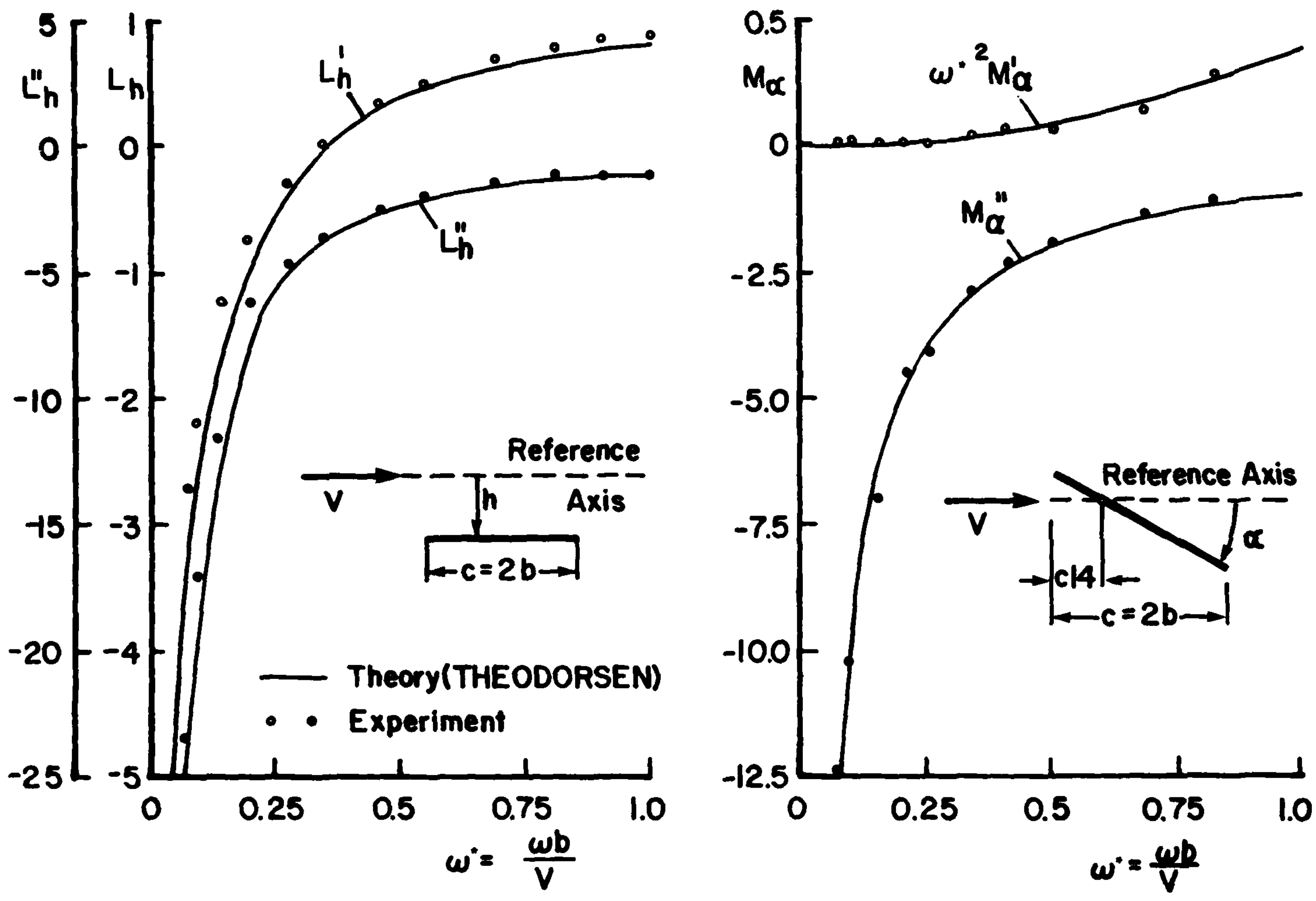


Figure 34 Unsteady Lift and Moment Coefficients on a Flat Plate in Plunge and Pitch

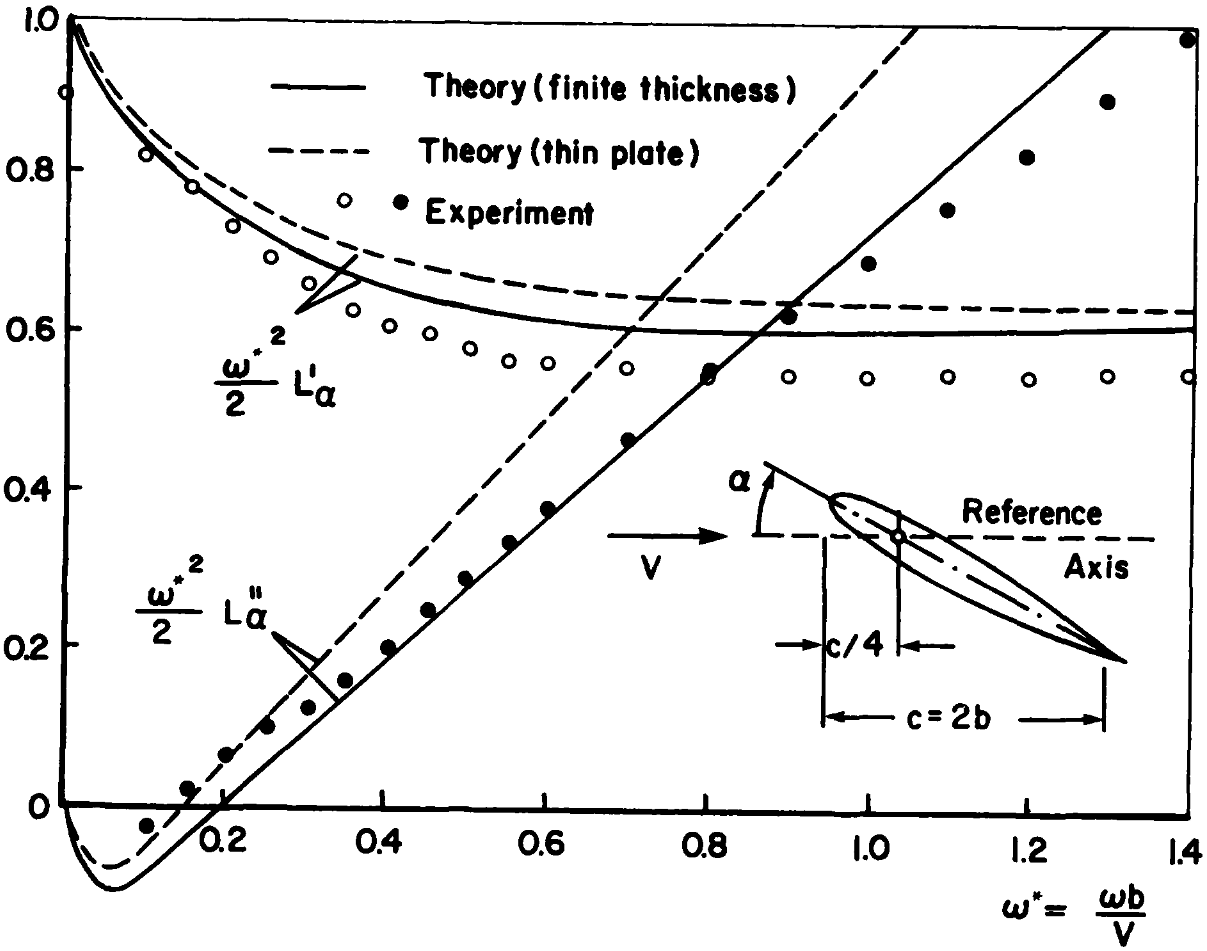


Figure 35 Flat Plate Oscillating in Pitch-Thickness Effects

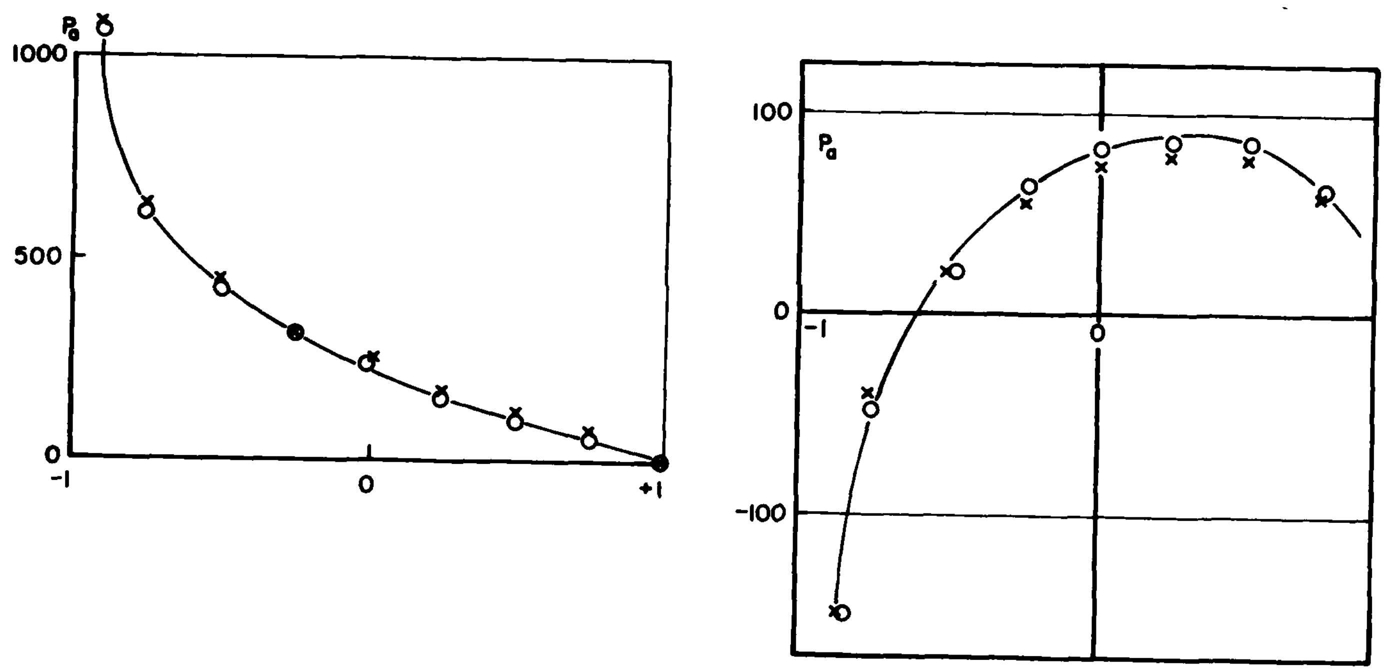


Figure 36 Chordwise Pressures on a Rectangular Wing by Matching the Theodorsen Function C(k)

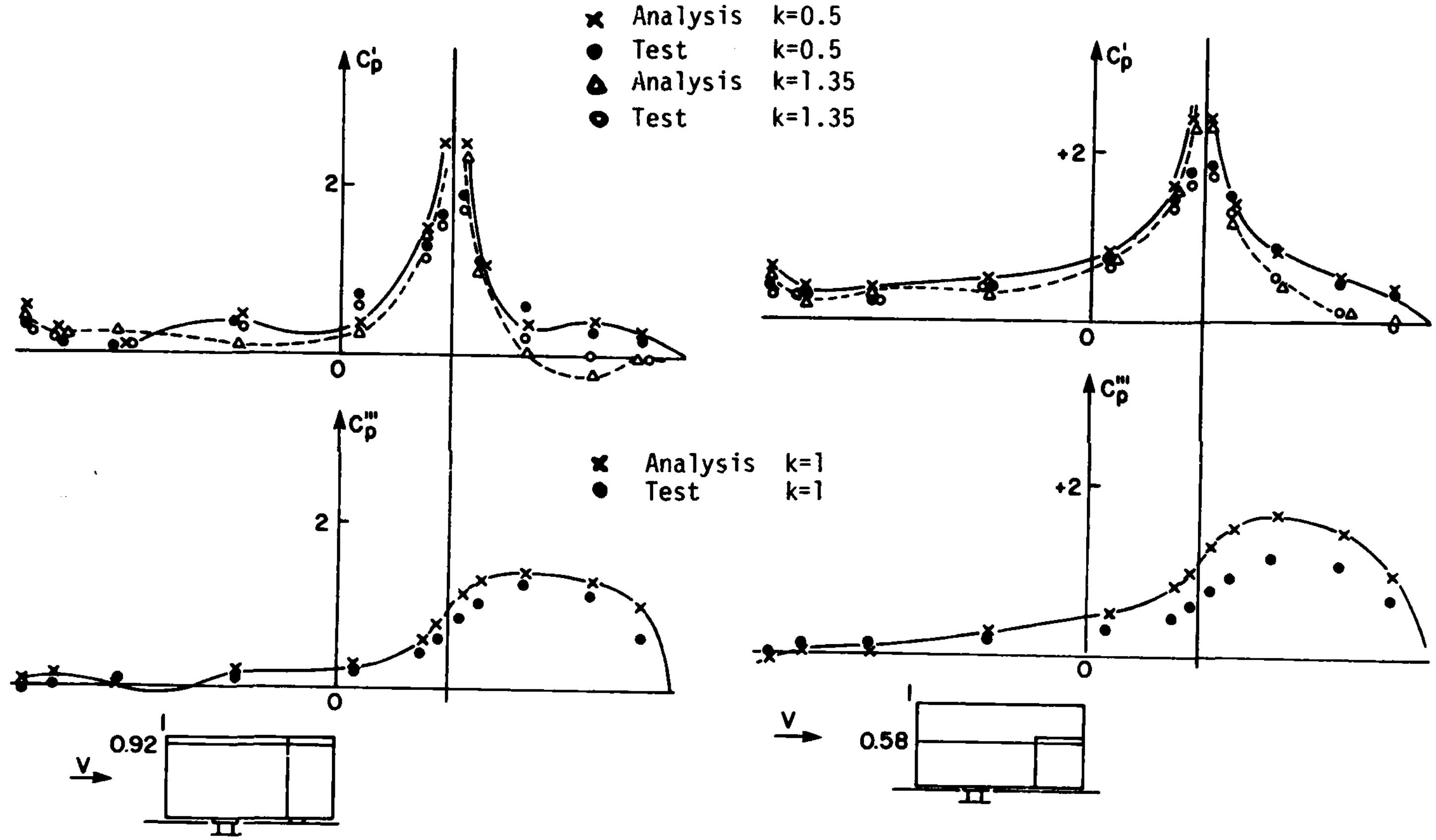


Figure 37 Low Aspect Ratio Wing-Control Surface

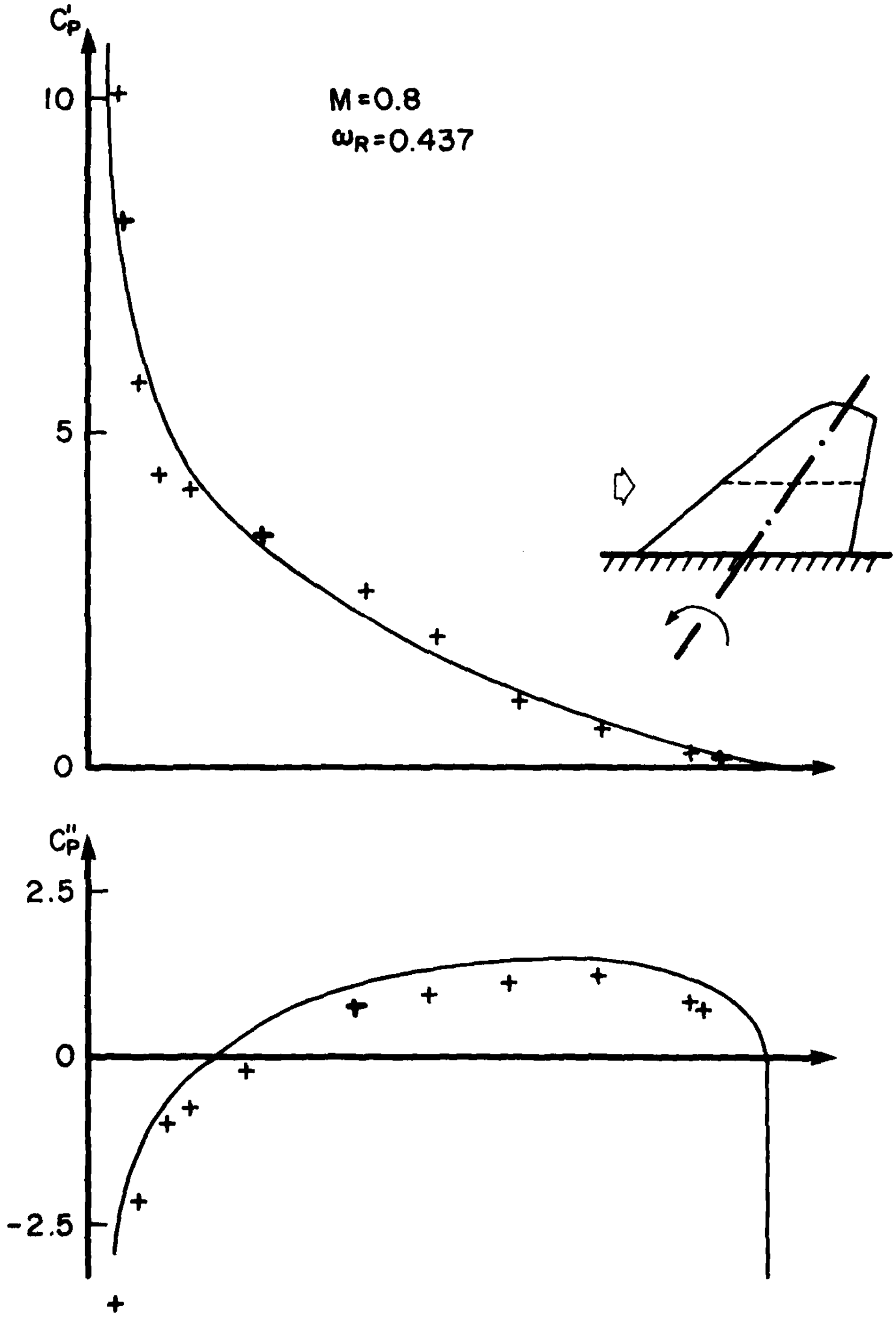


Figure 38 Trapizoidal Half-Wing Pitching About a Swept Axis

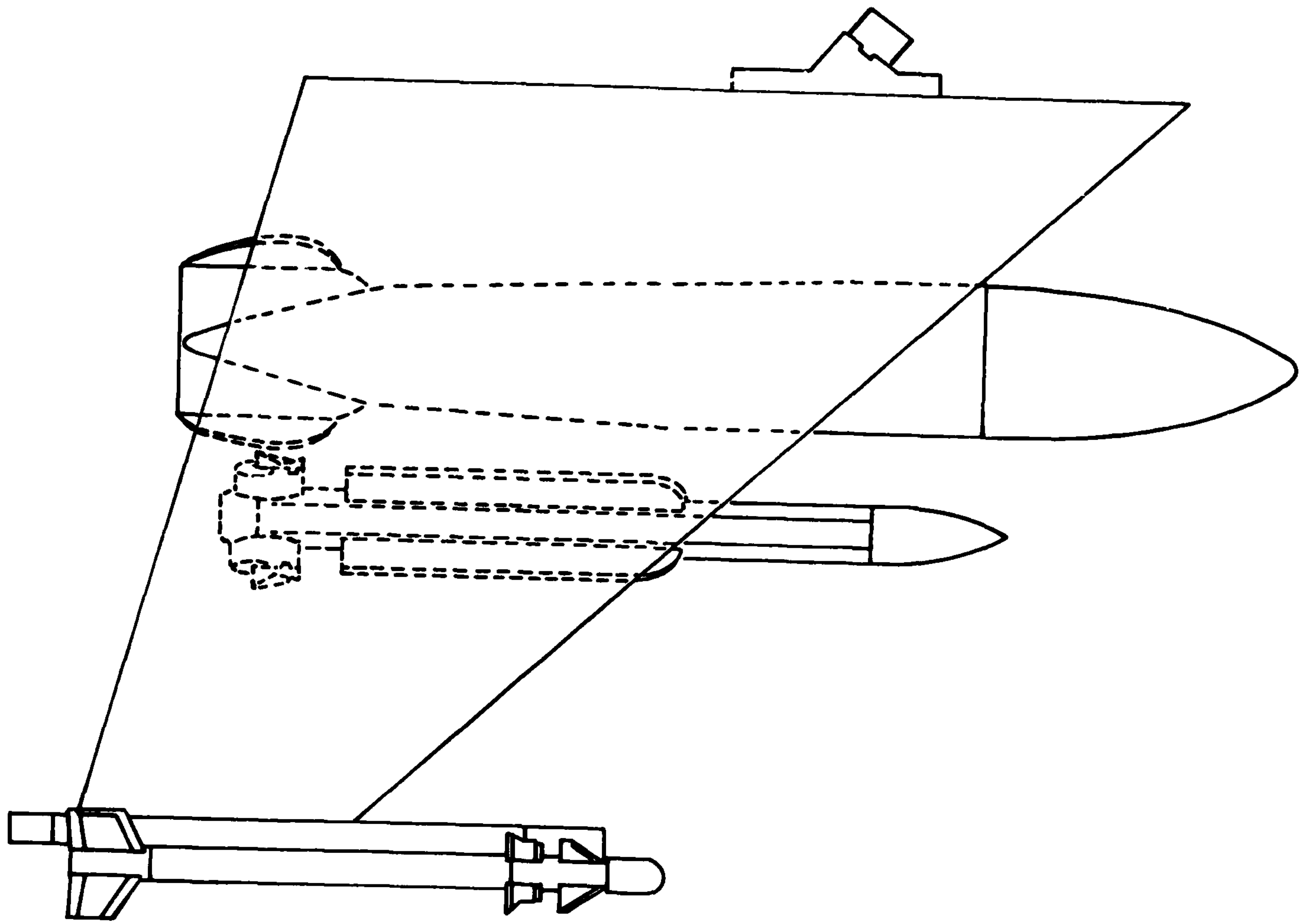


Figure 39 Mirage F-1 Wing with Camber and Twist Removed

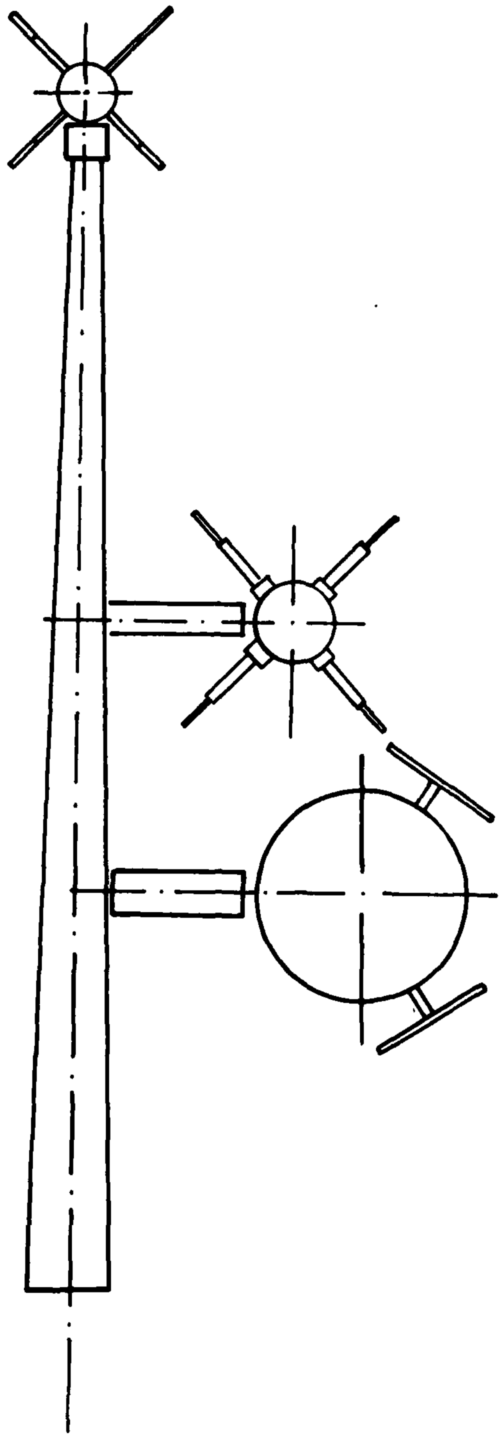


Figure 40 Mirage F-1 Wing Stores

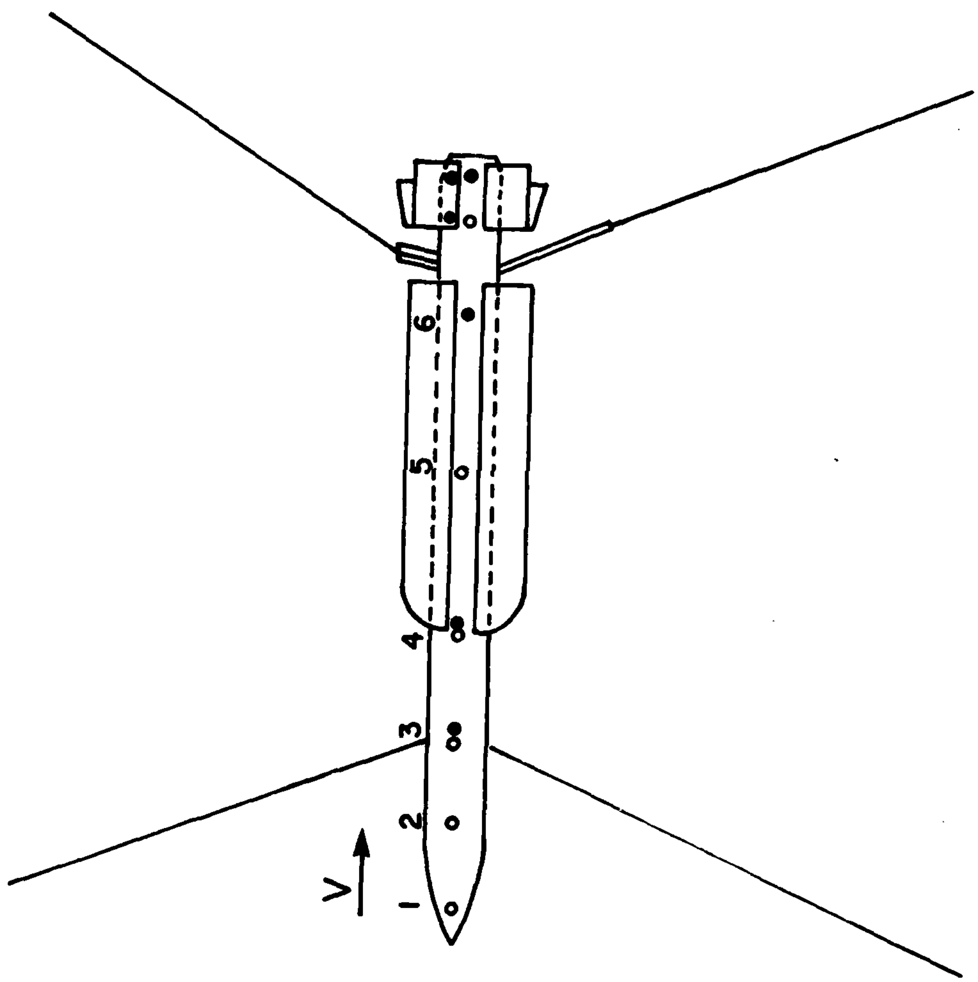


Figure 41 Isolated Store, Suspended and Oscillated in Pitch

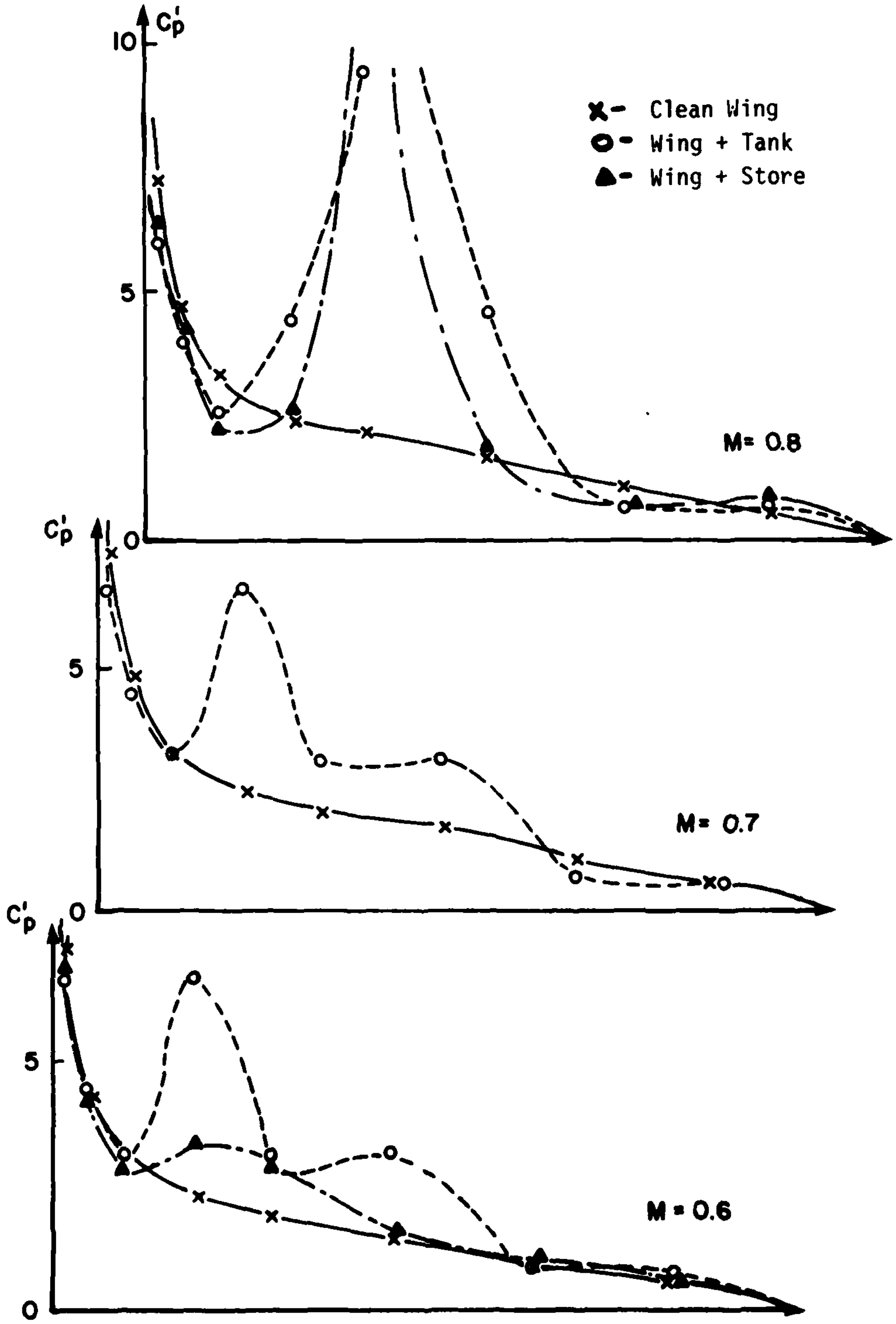


Figure 42 The Effect of Stores on Wing Pressures

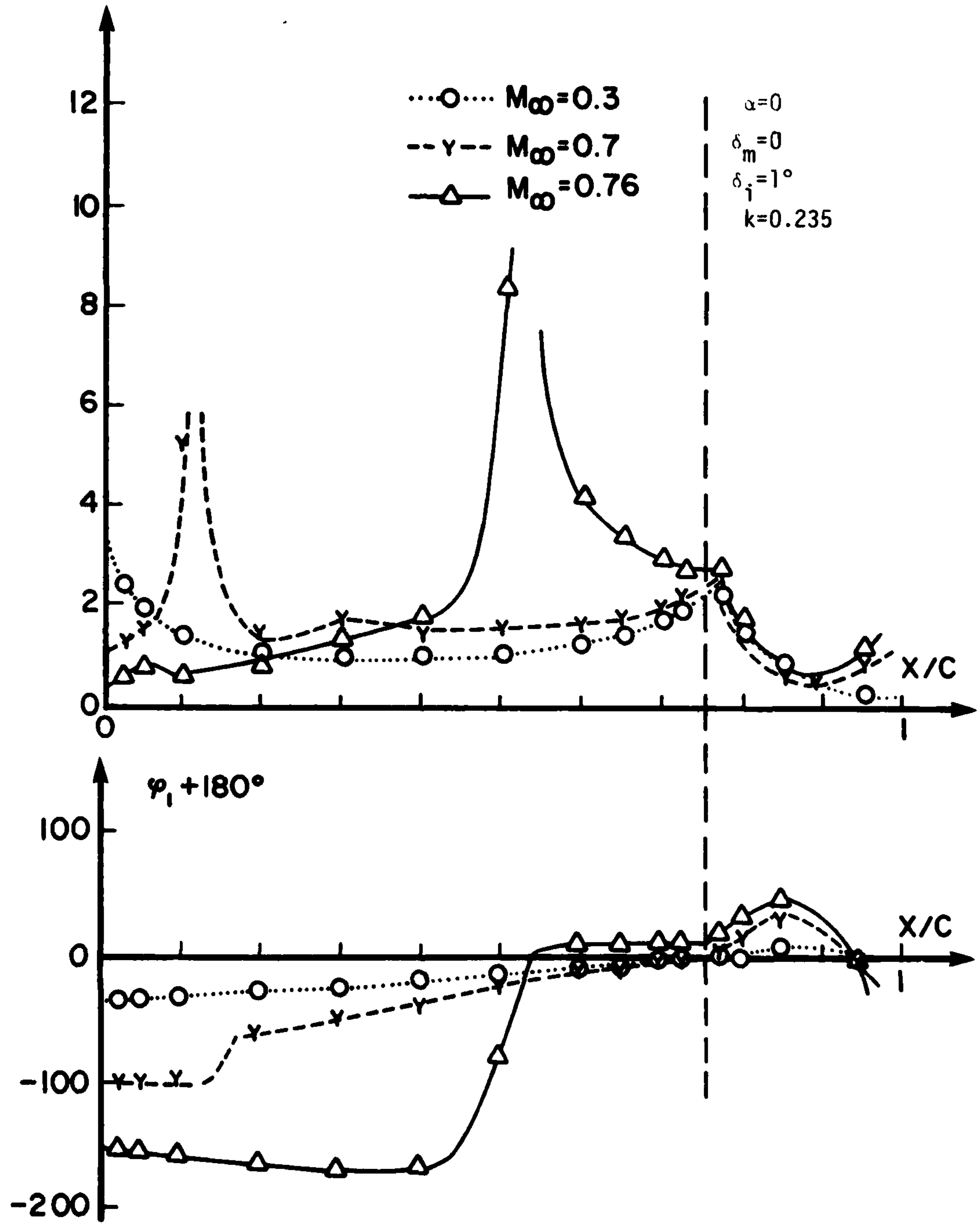


Figure 43 The Effect of Mach Number on Supercritical Airfoil Pressures for an Oscillating Flap

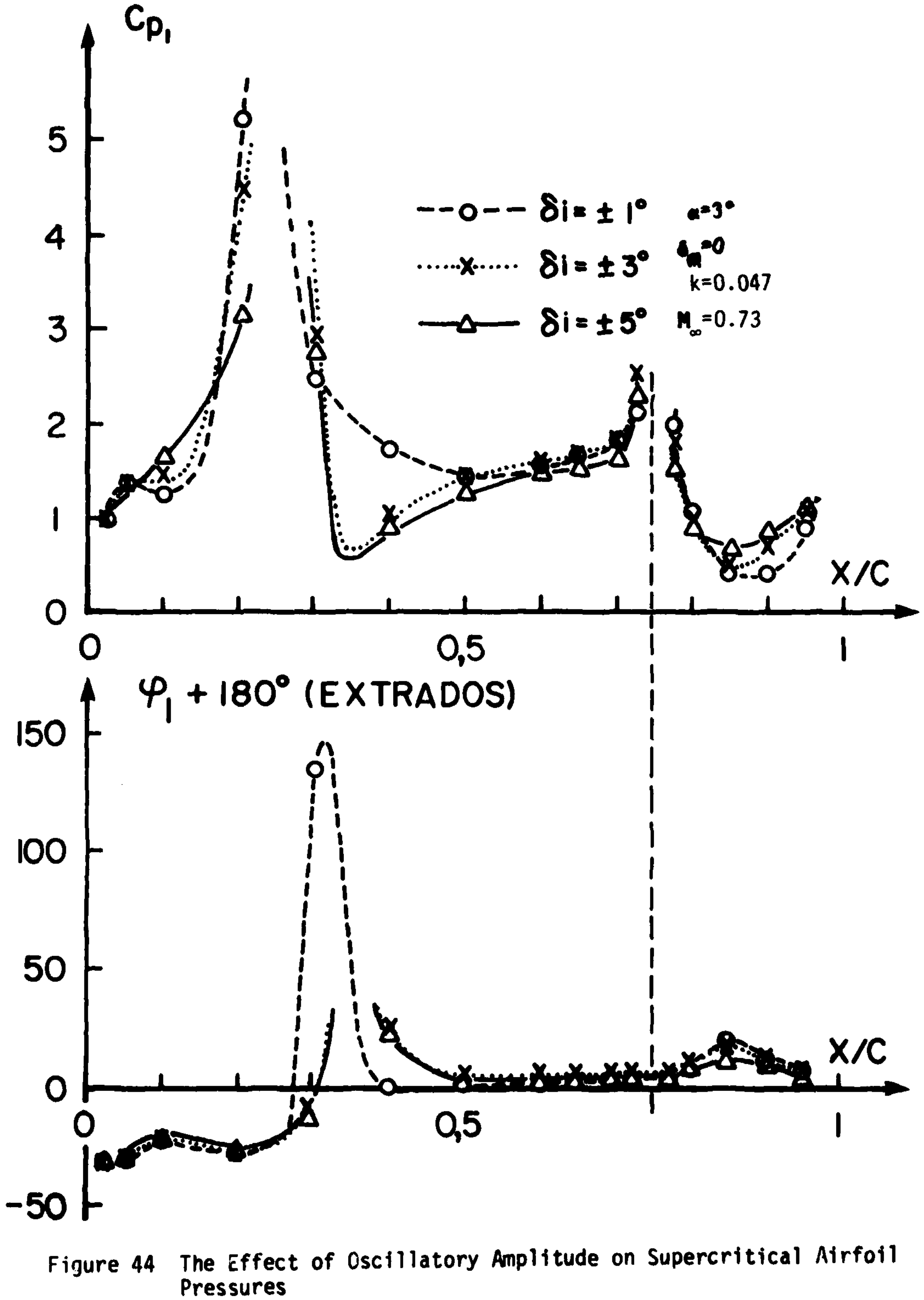


Figure 44 The Effect of Oscillatory Amplitude on Supercritical Airfoil Pressures

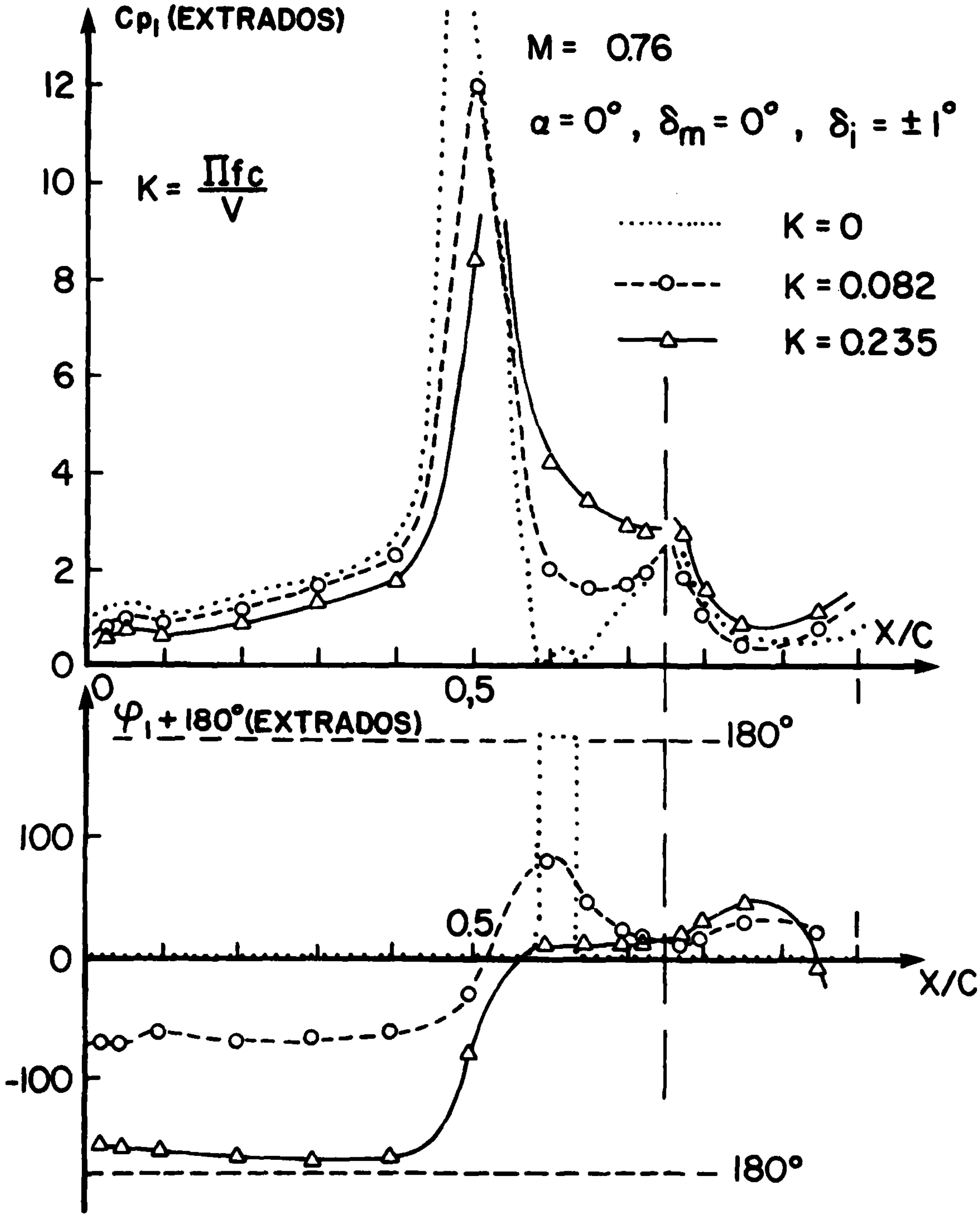


Figure 45 The Effect of Reduced Frequency on Supercritical Airfoil Pressures

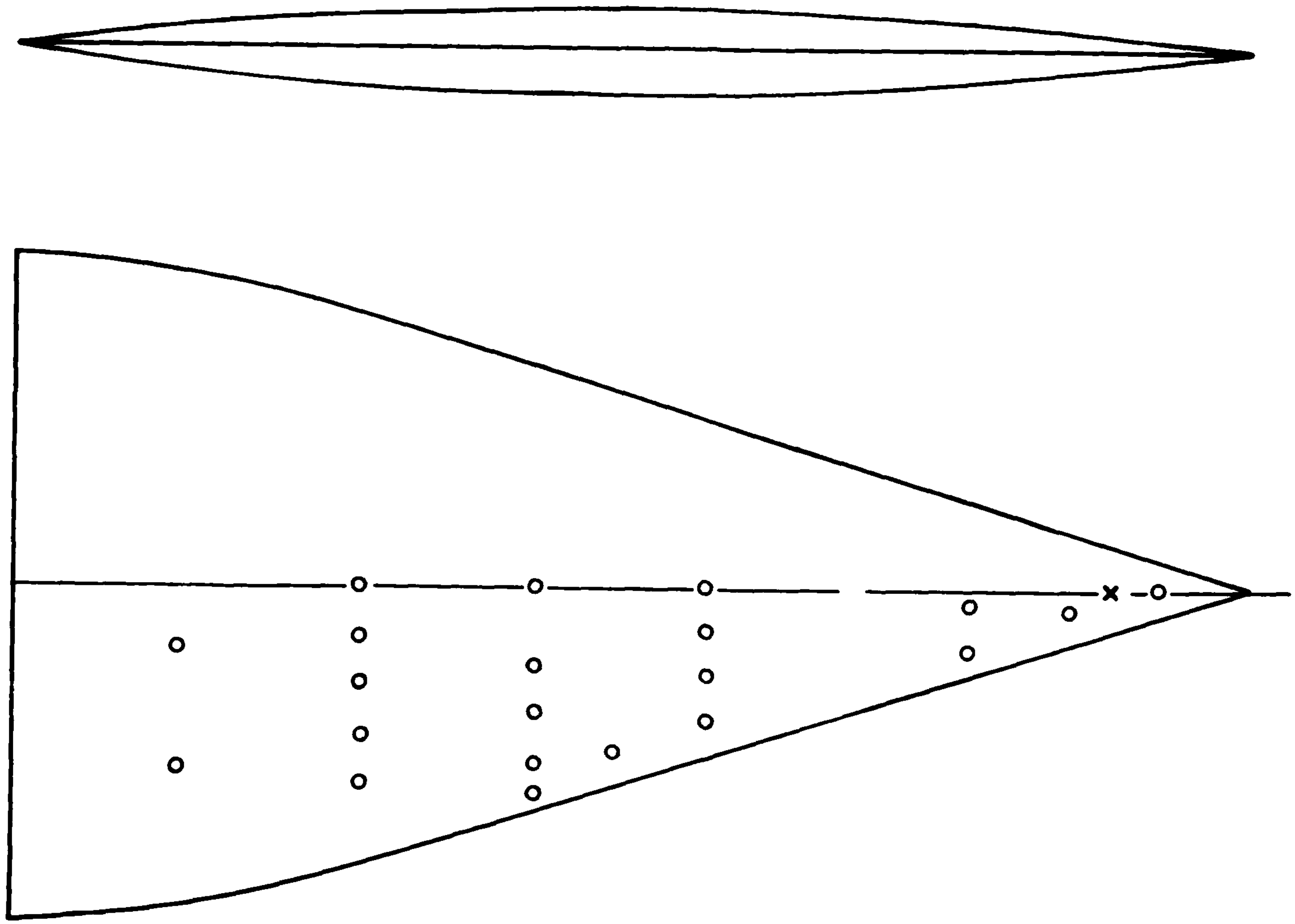


Figure 46 Slender Wing Oscillated in Chordwise Bending

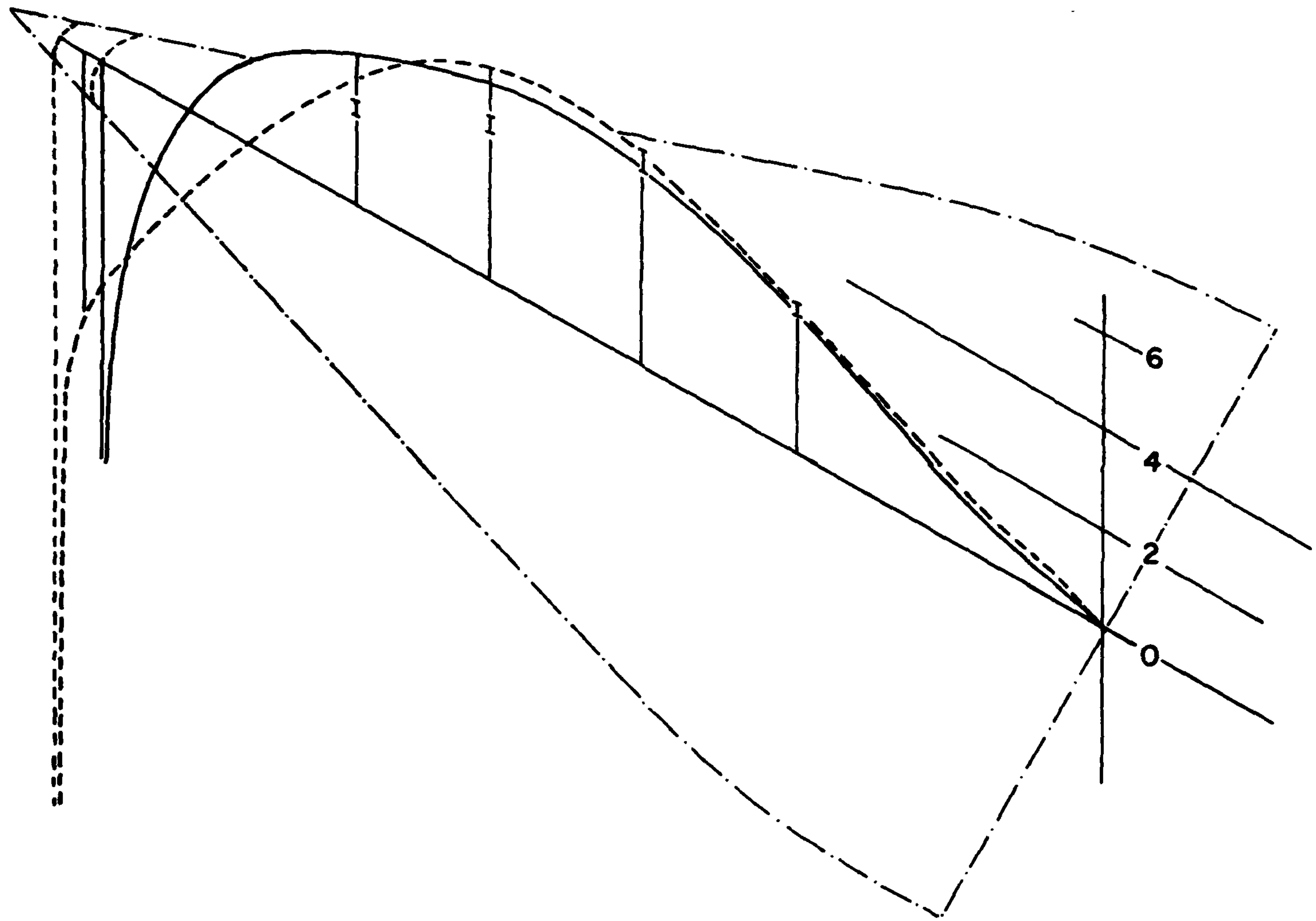


Figure 47 Calculated and Experimental Centerline Pressures in Chordwise Bending

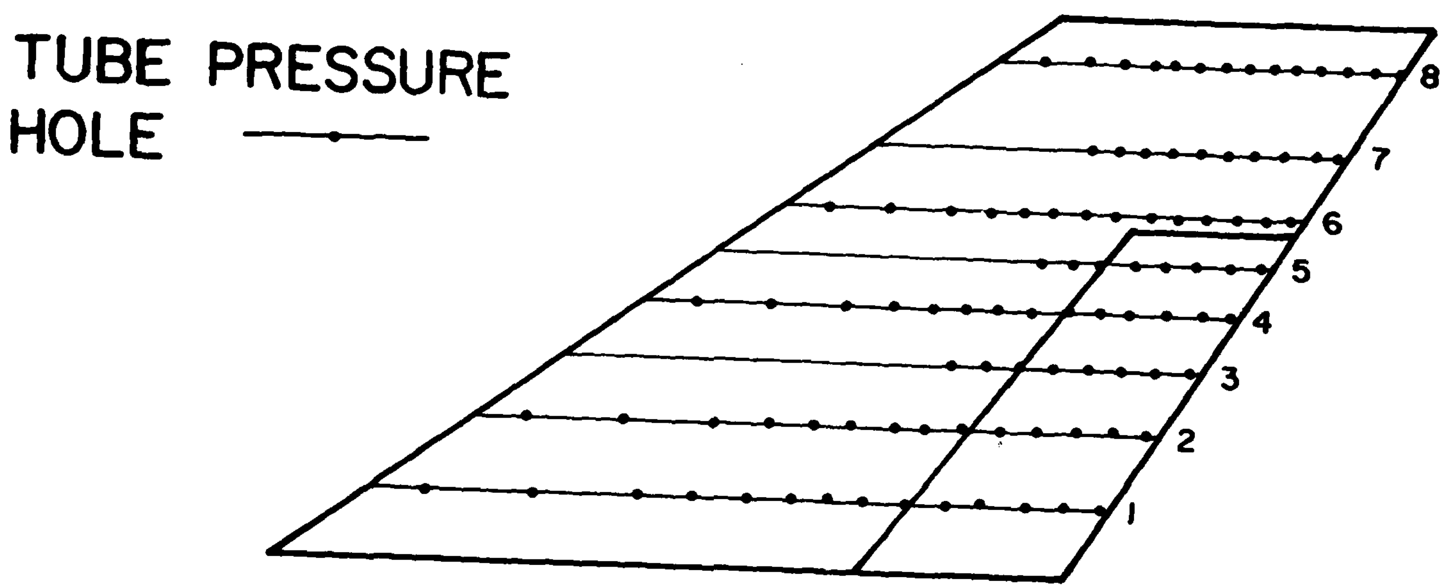


Figure 48 Rigid Wing with Oscillating Control Surface

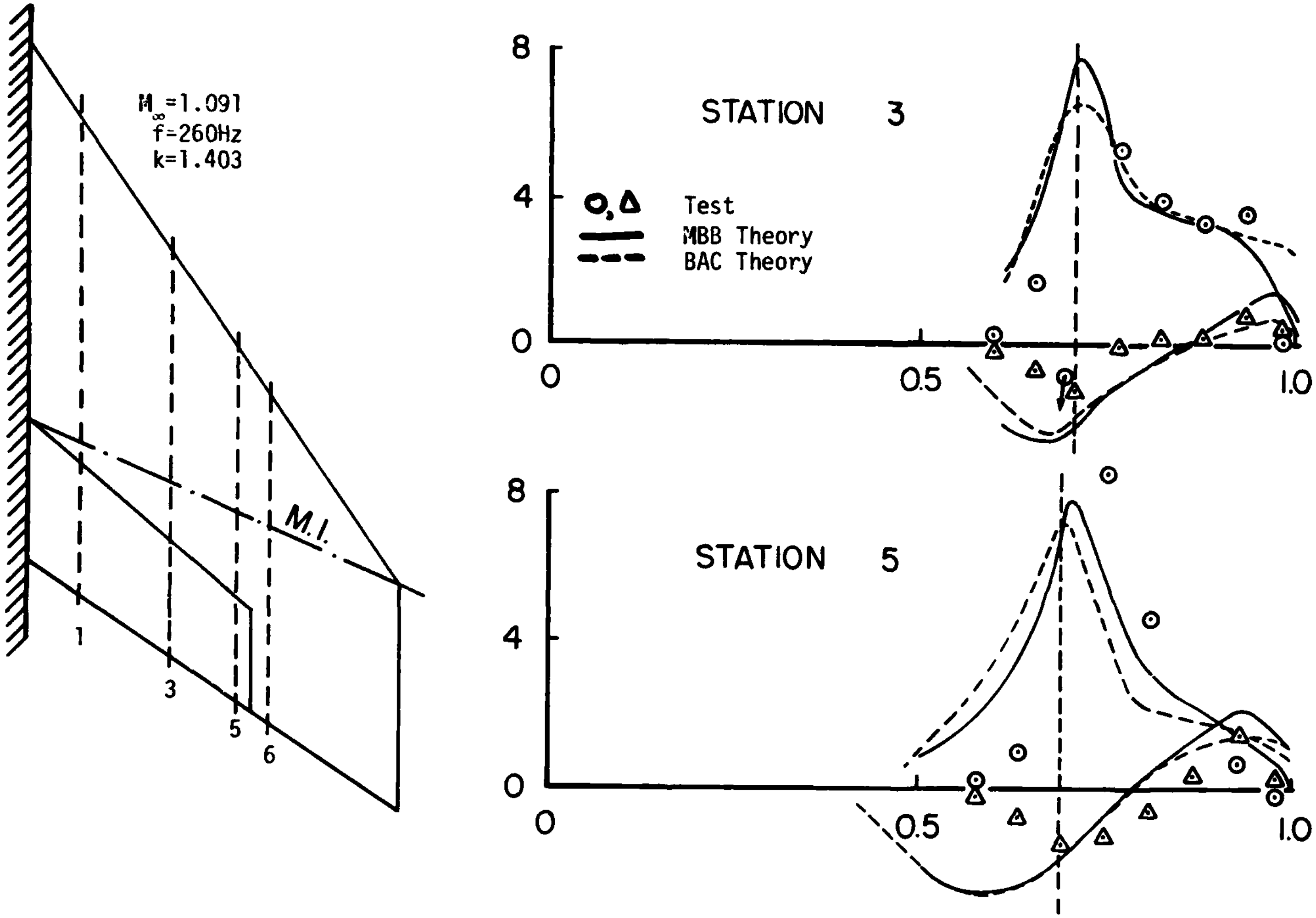


Figure 49 Supersonic Pressure Due to Control Surface Rotation

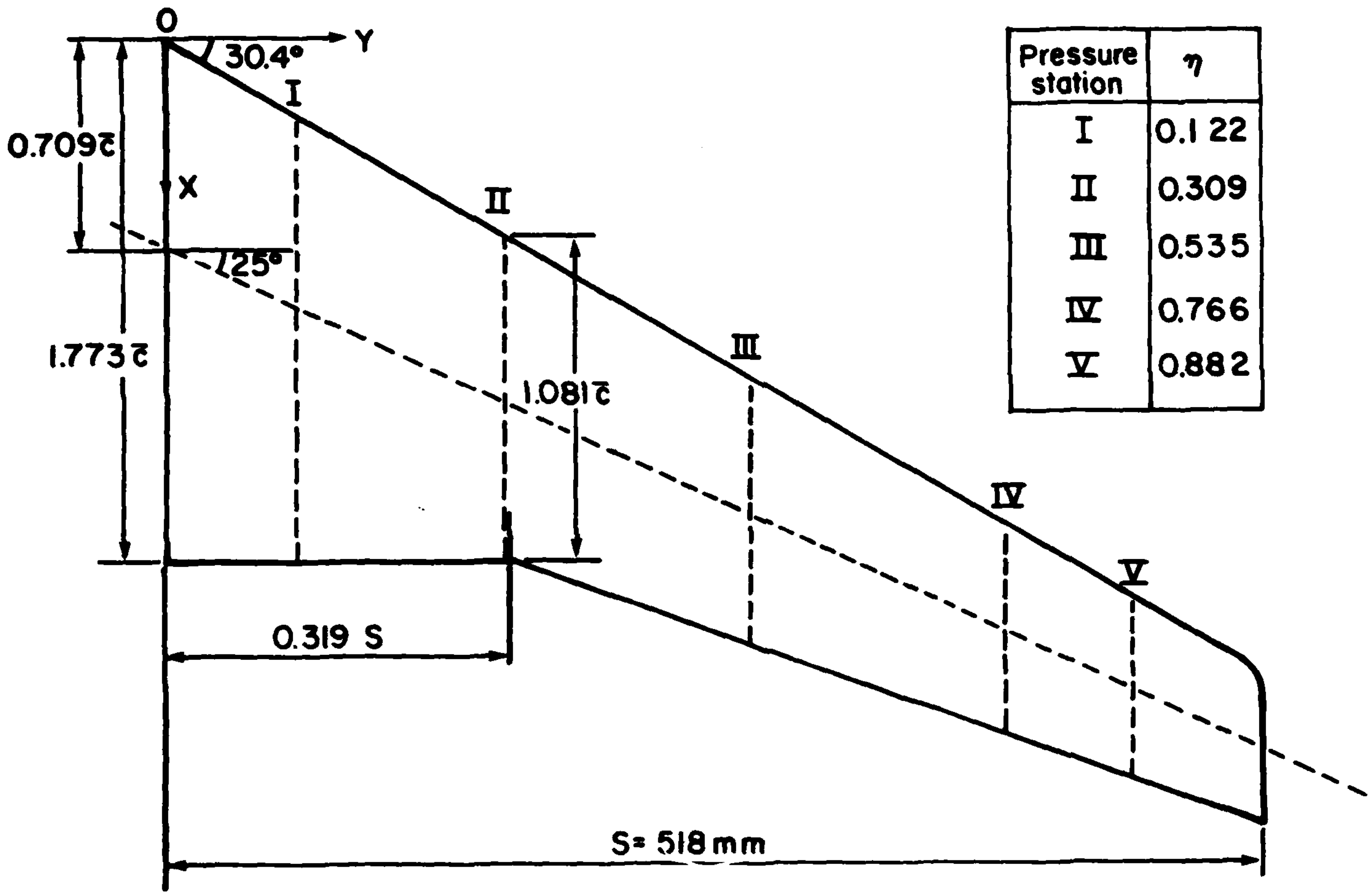


Figure 50 Transport Wing with Supercritical Airfoil Sections

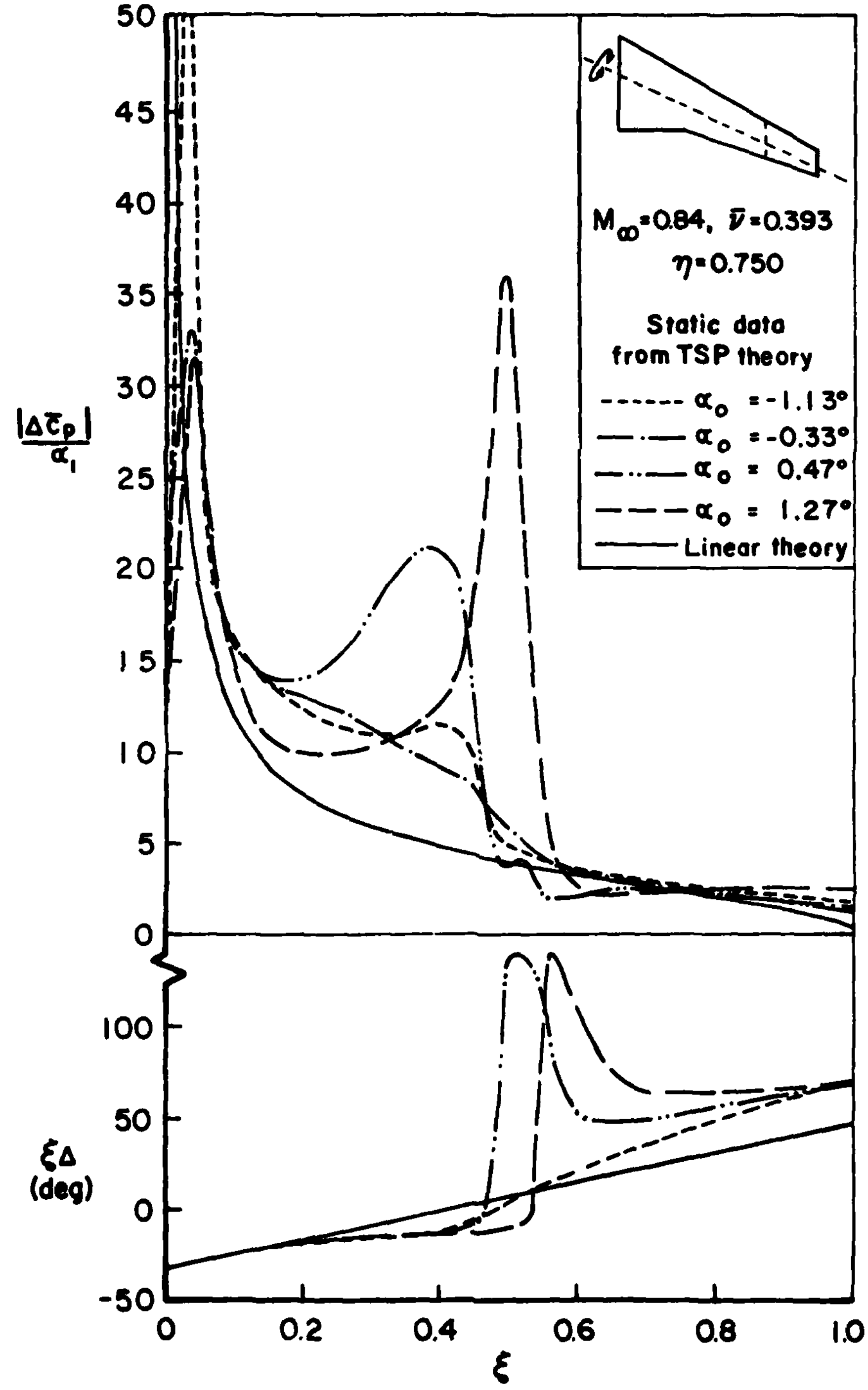


Figure 51 Effect of Mean Incidence on Oscillatory Pressures Due to Pitch

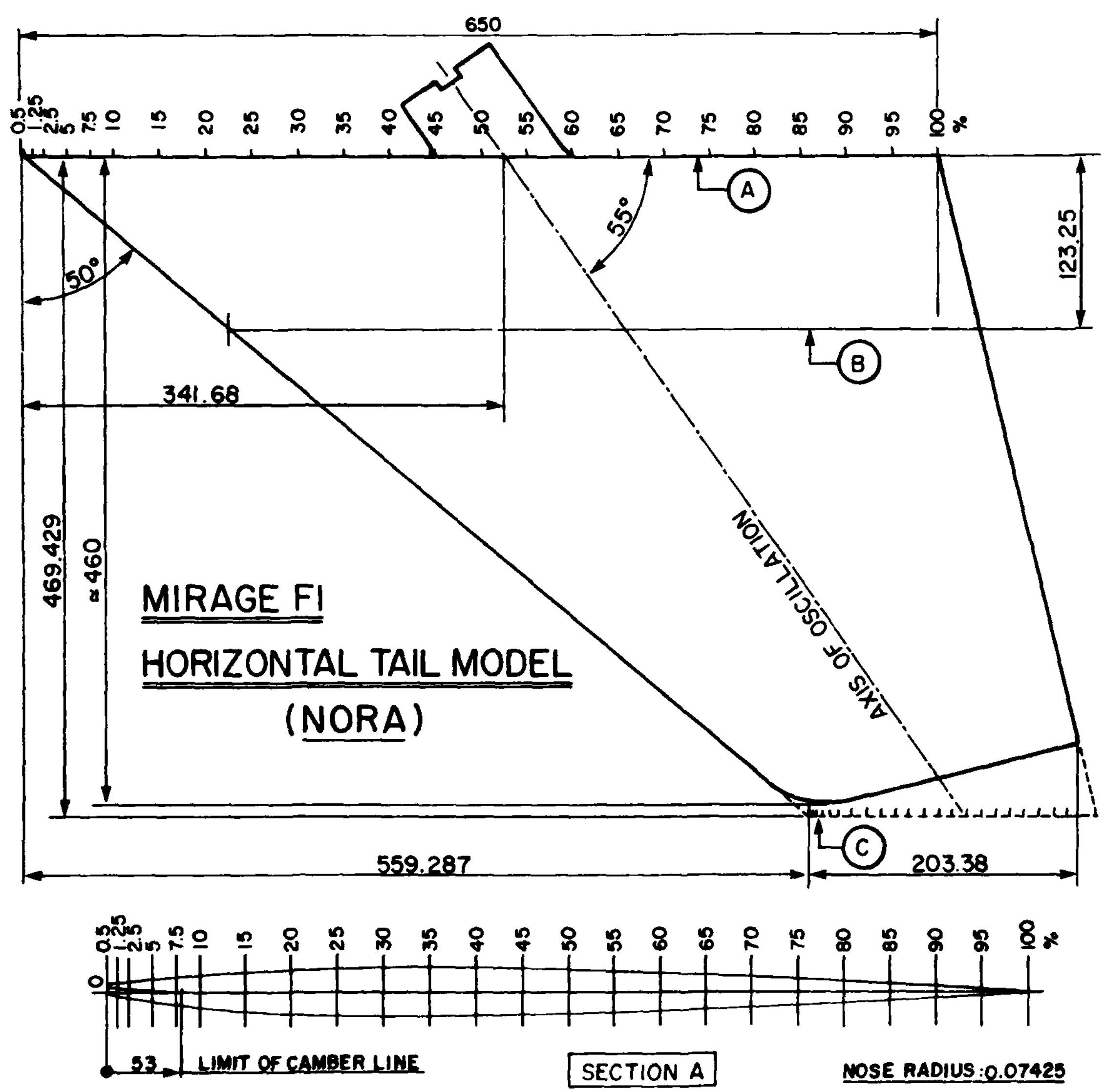


Figure 52 The NORA Mirage F-1 Taileron

TABLE 1

TEST VARIABLES FOR WING-TAIL MODELS

WING SWEEP ANGLE	25°, 40°, 70°
TAIL AFT POSITION	$0.5\ s_1 \leq X \leq 1.4\ s_1$ s_1 = wing semi-span at 25°, 40°, or 70°
TAIL VERTICAL POSITION	-10 mm, + 130 mm
TAIL DIHEDRAL	15°, 30°
ANGLE OF ATTACK	0°, 6°
WING FREQUENCIES	5, 10, 15 Hz
TAIL FREQUENCIES	5, 10, 15 Hz
MODES OF WING & TAIL OSCILLATIONS	Roll, Pitch
AMPLITUDE ABOUT ROLL & PITCH AXIS	0°, 3° - 1°, 5°
TUNNEL SPEED	20, 30 and 40 m/s